Executive Function and Language Control in Bilinguals with a History of Mild Traumatic Brain Injury

by

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ABSTRACT

Adults with a history of traumatic brain injury (TBI) often show deficits in executive functioning, which include the ability to inhibit, switch, and attend to task relevant information. These abilities are also essential for language processing in bilinguals, who constantly inhibit and switch between languages. Currently, there is no data regarding the effect of TBI on executive function and language processing in bilinguals. This study used behavioral and eye-tracking measures to examine the effect of mild traumatic brain injury (mTBI) on executive function and language processing in Spanish-English bilinguals. In Experiment 1, thirty-nine healthy bilinguals completed a variety of executive function and language processing tasks. The primary executive function and language processing tasks were paired with a cognitive load task intended to simulate mTBI. In Experiment 2, twenty-two bilinguals with a history of mTBI and twenty healthy control bilinguals completed the same executive function measures and language processing tasks. The results revealed that bilinguals with a history of mTBI show deficits in specific executive functions and have higher rates of language processing deficits than healthy control bilinguals. Additionally, behavioral and eye-tracking data suggest that these language processing deficits are related to underlying executive function abilities. This study also identified a subset of bilinguals who may be at the greater risk of language processing deficits following mTBI. The findings of this study have a direct impact on the identification of executive function deficits and language processing deficits in bilinguals with a history mTBI.

DEDICATION

This work is dedicated to my mom and dad who taught me the importance of education, hard work, and intellectual curiosity. And to my husband, Rohan, who graciously put up with a lot of late nights at the office and frozen meals. It takes a village to raise a doctoral student, and I am grateful to all of you beyond words.

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Executive Function and Language Control in Bilingual Individuals with a History of Brain Injury

The majority of the world's population is bilingual (Bialystok, Craik, & Luk, 2012; Marian, 2008). In the United States, approximately 25% of individuals are bilingual and the proportion is higher for urban areas, college educated individuals, and border states, such as Arizona (40%) (U.S. Census Bureau, 2011). While there is no established definition of bilingualism, most researchers agree that bilinguals possess a "functional fluency" in two languages (Bialystok, 2001) or can communicate in two languages in daily life (Grosjean, 1989).

The ability to communicate effectively in two languages may shape bilingual cognition in important ways. For example, bilinguals perform better than monolinguals on tasks that require switching especially if they frequently switch between two languages (e.g., Prior & Gollan, 2011; Prior & MacWhinney, 2009). Other studies have shown differences between bilinguals and monolinguals on tasks that require inhibition or monitoring multiple stimuli (see Bialystok, Craik, Green, & Gollan, 2009 for a review). For example, bilinguals may inhibit interference from distracting stimuli more efficiently than monolinguals (e.g., Costa, Hernández, & Sebastián-Gallés, 2008; Friesen, Latman, Calvo, & Bialystok, 2014; Hilchey & Klein, 2011). Bilinguals may also be more efficient at monitoring and classifying auditory and visual information presented simultaneously (e.g., Bialystok, Craik, & Ruocco, 2006). These differences in performance may be due to bilinguals' constant selection and suppression of competing cross-language activations. Psycholinguistic studies have shown that a bilinguals are not able to "shut off" one language and both languages are always active (e.g., De Groot, Delmaar, & Lupker, 2000; Dijkstra, Van Jaarsveld, & Ten Brinke, 1998; Spivey, & Marian, 1999). Yet, bilinguals are able to successfully communicate in one language without constant intrusion from the contextually irrelevant language. This indicates that they use cognitive mechanisms to regulate cross language competition. These cognitive mechanisms may be domain general in nature (i.e., not specific to language) (e.g., Garbin et al., 2010).

These general mechanisms may be affected if a bilingual acquires a neurological injury or disorder. Monolingual individuals who experience a brain injury, especially affecting the frontal lobe, may show deficits in the ability to sustain attention, mentally shift their attention between tasks, hold multiple items memory, or suppress interference from distractors (e.g., Eslinger, Grattan, & Geder, 1995; Kennedy et al., 2008; Miyake et al., 2000). In addition to these deficits, bilinguals may also experience deficits in their ability to regulate cross-language activations. However, no studies have investigated the impact of traumatic brain injury on bilingual cognition or bilingual language processing. The purpose of the present study was to examine how concussion or mild traumatic brain injury impacts bilingual cognition and language processing.

Bilingual Language Processing and Language Control

For bilinguals, both languages are constantly active (e.g., Duñabeitia, Perea, & Carreiras; 2010; Illes et al., 1999; Spivey & Marian, 1999). Studies have shown that a bilingual's languages are integrated and lexical items across languages are co-activated whether items are orthographic (e.g., Dijkstra et al., 1998; Duñabeitia, Perea, & Carreiras, 2010; Libben & Titone, 2009) or auditory in nature (e.g., Marian & Spivey, 2003; Spivey & Marian, 1999). Additionally, neuroimaging evidence has demonstrated overlapping activation for both languages in regions associated with language production and comprehension, such as the left inferior frontal gyrus, the left dorsolateral prefrontal gyrus, superior temporal gyrus, and the left supplementary motor area (e.g., Chee, Tan, & Thiel, 1999; Illes et al.; Marian, Spivey, & Hirsch, 2003; Zou et al., 2012).

To communicate efficiently, bilinguals must possess one or multiple mechanisms to inhibit cross language co-activation. Green's (1998) Inhibitory Control (IC) model assumes multiple levels of control in bilingual language processing. According to the IC model, each lexical concept is associated with a language tag, denoting language membership. When a concept becomes active, lexical items in both languages become active. The item in the non-target language is reactively inhibited via the language tag. The IC model also posits a task schema which can be constructed or adapted to inhibit cross-language activation. This schema regulates output from the lexico-semantic system by inhibiting the non-target language in favor of the target language through top-down control. For example, if a Spanish-English bilingual is asked to name items in Spanish, the task schema would be "name words in Spanish." If this bilingual activates the concept of a dog, both "perro" and "dog" become activated. Perro is tagged as Spanish and dog is tagged as English. The item with an English tag is then inhibited.

Green and Abutalebi (2013) proposed that bilinguals use multiple adaptive control mechanisms to resolve the conflict between competing language activations, referred to as *language control*. Green and Abutalebi describe eight control processes that are responsible for language control in different linguistic contexts. These processes are: goal maintenance, interference control (which involves conflict monitoring and interference suppression), salient cue detection, selective response inhibition, task disengagement, task engagement, and opportunistic planning. Goal maintenance refers to maintaining the goal to speak in one language rather than the other. To accomplish this, conflict monitoring and interference suppression are necessary. Interference suppression can occur at two levels, either at the task schema or at the lexico-semantic system, consistent with the IC model. Salient cue detection is used when the speaker must switch languages with different conversational partners. The control process of selective response inhibition allows a bilingual to inhibit an ongoing in favor of a more relevant response. This relies on stopping the current language (task disengagement) and engaging the new language (task engagement). Lastly, opportunistic planning is defined as the ability to flexibly adapt the words of one language into the syntactic framework of another.

The degree to which each control process is recruited depends on the demands of the linguistic context. Green and Abutalebi argue that goal maintenance, conflict monitoring, and interference suppression are necessary in all linguistic contexts, even when a bilingual is required to communicate in only one language. These control processes allow the bilingual to effectively communicate in one language without intrusion from the other. In contexts where bilinguals may switch between two languages, salient cue detection, selective response inhibition, task disengagement and engagement are recruited. Opportunistic planning is used primarily in a context where two languages are intermixed within single utterances. Although the IC model and adaptive control hypothesis are primarily intended to describe language control, the assumptions of these models have implications for general cognitive function. Green and Abutalebi suggest that cognitive differences between bilinguals and monolinguals may arise because language control is exercised by common cognitive control mechanisms not specific to language control.

Studies investigating cognitive control of two languages have provided evidence in support of the IC model and adaptive control hypothesis and suggest that bilinguals use multiple neural regions in language control. These regions include the prefrontal cortex, anterior cingulate cortex (e.g., Abutalebi et al., 2008), inferior parietal lobule (Mechelli et al., 2004), the basal ganglia (Lehtonen et al., 2005), and the caudate nucleus of the basal ganglia (e.g., Crinion et al., 2006). In bilingual language control, the prefrontal cortex is involved in selecting which language is to remain active, inhibiting the non-target language, and retrieving words in the appropriate language (Abutalebi, 2008). Both the prefrontal cortex and the anterior cingulate cortex are active when translating from one language into another or switching between languages (e.g., Abutalebi el al. 2008; Hernandez, 2009). The inferior parietal lobule may be involved in articulatory planning and word production and may be particularly active when bilinguals communicate in their less dominant language or switch between languages (Abutalebi & Green, 2007; Mechelli et al., 2004). The caudate nucleus may play a role in monitoring the language in use and in detecting language switching in the environment (e.g., Abutalebi, 2008; Crinion et al, 2006). The basal ganglia may be involved in suppressing competing responses (e.g., Lehtonen et al., 2005). If a bilingual acquires a neurogenic impact to one or more of these regions, they are likely to show deficits in language processing and language control. For example, a bilingual who has an acquired subcortical lesion that affects the basal ganglia, or more specifically, the caudate nucleus, may exhibit spontaneous language switching and mixing (e.g., Abutalebi, Miozzo, & Cappa, 2000).

Traumatic Brain Injury and Executive Function

Approximately 1.4 million individuals sustain a traumatic brain injury (TBI) every year and approximately 80% of those are diagnosed with mild traumatic brain injury (mTBI) (Faul, Xu, Wald, & Coronado, 2010; Langlois, Rutland-Brown, Thomas, 2004). Broadly, TBI is defined as "an alteration in brain function…caused by an external force" (Menon, Schwab, Wright, & Mass, 2010, p. 1638). An alteration in brain function can include one or more of the following symptoms: loss of consciousness, loss of memory, loss of balance, change in vision, sensory deficits, confusion, disorientation, dizziness, headache, or nausea (Menon et al., 2010; Malec et al., 2007). A TBI is classified as mild if loss of consciousness is shorter than 30 minutes and loss of memory is shorter than 24 hours. Traumatic brain injury can impact one or multiple cortical and subcortical regions. The most common cortical areas affected are the frontal and temporal lobes (e.g., Gentry, Godersky, & Thompson, 1988; Rees et al., 2007; Umile, Sandel, Alavi, Terry, & Plotkin, 2002), but lesions may also occur in parietal lobes, occipital lobes, cerebellum, thalamus, caudate nucleus, putamen, and anterior cingulate (e.g., Gentry et al., 1987; Umile et al., 2002).

Deficits in executive function are common following TBI (e.g., Eslinger et al., 1995; Hunt, Turner, Polatajko, Bottari, & Dawson, 2013; Kennedy et al., 2008; Miyake et al., 2000). Executive function (EF) refers to a set of cognitive processes responsible for the complex control of thoughts and actions. Individuals rely on EF when inhibiting interference from distracting stimuli, inhibiting prepotent responses, switching attention between multiple tasks, planning and organizing a sequence of events, reasoning, problem solving, and holding multiple task relevant goals in working memory (e.g., Garner, 2009; Miyake et al., 2000).

In a meta-analysis, Dimoska-Di Marco, McDonald, Kelly, Tate, and Johnstone (2011) investigated interference inhibition and response inhibition in individuals with TBI. Response inhibition was measured using go/no-go and stop signal tasks and required participants to withhold a response. In the go/no-go or stop-signal task, participants were required to press a key for all trials except when a specific cue was present. Interference inhibition was measured using the Stroop task and required participants to inhibit conflict arising from two competing stimuli. In the Stroop task, participants were asked to name the color of a printed word (e.g., the word blue printed in red ink) while suppressing or inhibiting reading the word. Dimoska-Di Marco et al. found that there was a significant difference between TBI patients and healthy controls for response inhibition tasks, but not for interference inhibition. The authors concluded that the ability to control interference arising from conflicting information may not be impaired in individuals with TBI. However, Dimoska-Di Marco et al., argue that this population does have deficits with withholding manual responses. Similarly, Swick, Honzel, Larsen, Ashley and Justus (2012) found that individuals with mTBI have significant impairments in response inhibition using a go/no-go task. Dimoska-Di Marco et al., conclude that impairments in response inhibition may underlie more severe disinhibition in patients with more moderate to severe TBI. Indeed, these individuals often exhibit inappropriate behaviors due to disinhibition (e.g., Kim, 2002; Ylvysaker, Turkstra, & Coelho, 2005).

Individuals with mTBI may experience difficulty when switching their attention between different tasks. Caeyenberghs and colleagues (2014) investigated task switching ability in participants with TBI and healthy controls using a trail making task. The trail making task contained the numbers from 1 to 12 and letters from A to L. Participants were asked to connect the symbols by alternating the sequence between numbers and letters. Individuals with a history of TBI were slower to complete the task, made more errors, and showed a greater cost when alternating between symbols compared to healthy controls. Further, performance on the trail making task was related to prefrontal cortex activity in the TBI group. The authors concluded that TBI affects individuals' abilities to shift attention between tasks which is directly related to underlying efficiency in neural activation. Similarly, Leunissen et al. (2014) also found decreased task switching performance in individuals with TBI which was correlated with white matter integrity. Caeyenberghs and colleagues argue that subtle deficits in task switching ability are related to flexible adjustments of behavior, commonly impaired in individuals with acquired TBI.

Krawczyk et al. (2010) investigated analogical reasoning abilities in patients with TBI. Analogical reasoning requires the understanding of relationships among two or more elements and applying that relationship onto other pairs of elements. In their study, Krawczyk et al. asked participants to study images and identify a relationship among the items in the first picture. Participants then had to identify a similar relationship among items in a second picture. The authors found that individuals with TBI performed significantly worse than healthy individuals. The authors concluded that TBI results in deficits in reasoning ability which may lead to deficits in solving higher complexity problems.

Other studies have reported that individuals with TBI may have deficits in reasoning abilities. For example, Vas Spence, and Chapman (2015) examined gist reasoning differences between a group of individuals with TBI and a group of healthy controls. Gist reasoning refers to the ability to abstract meaning from information that is not explicitly stated. Participants read stories and were asked to provide a synopsis of ideas not explicitly stated in the text. The authors controlled for group differences in EF, such as working memory, inhibition, and task switching. Vas and colleagues found that, even after controlling for EF differences, the TBI group performed significantly worse than healthy controls on the gist reasoning measure. Further, individuals who performed worse on gist reasoning also reported greater difficulty with daily interactions in professional or social environments. The authors concluded that individuals who experience TBI have deficits in complex EFs, such as gist reasoning, and these deficits are related to daily functional outcomes.

Complex reasoning abilities that are representative of daily life skills may also be impacted by mTBI. MacDonald and Johnson (2005) investigated complex verbal reasoning abilities and problem solving in patients with mTBI and healthy patients. In their study, participants read a brief stories containing different problems. For example, participants were required to plan a children's event given budget and time restrictions. Participants were required to gather the important facts and eliminate the irrelevant facts to come up with the best solution. MacDonald and Johnson found that patients with a history of mTBI performed significantly worse than healthy controls. The authors concluded that individual with acquired mTBI have deficits in complex verbal reasoning and problem solving abilities.

Individuals with acquired TBI may also show deficits on tasks that require them to hold multiple items in memory, such as working memory tasks. Dean and Sterr (2013) investigated performance on an n-back task in individuals with and without mTBI. Participants were asked if a current number matched a number that was presented one, two, or three trials back. Task difficulty increased as the number of n-back trials increased. The authors found that participants with a history of mTBI made significantly more errors than the healthy controls at every level of difficulty. Similarly, Slovarp, Azuma, and LaPoint (2012) also found that individuals with TBI performed worse on an n-back task. Dean and Sterr concluded that working memory deficits are present in patients with a history of mTBI even years after the injury.

Terry et al. (2012) also examined whether individuals with mTBI showed deficits when required to hold multiple items in memory in the face of distraction. Participants with mTBI and healthy controls completed the operation span task, a complex working memory task (Turner & Engle, 1989). Participants were shown a two-step math equation to verify and an item to remember. This item can be a word, letter, or digit. Terry et al. found that patients with mTBI performed significantly worse on the operation span task compared with healthy controls. The authors concluded individuals with mTBI show deficits in the ability to hold multiple items in memory.

However, individuals with mTBI do not show deficits across all types of memory tasks. For example, individuals with mTBI perform as well as healthy controls on simple span memory tasks (e.g., Anderson & Knight, 2010; Ozen, Skinner, Fernandez, 2010). In simple span tasks, such as a digit span task, participants are required to simply repeat a short list of items. This suggests that individuals with mTBI do not have difficulty with simple span memory, but they do show deficits in more complex or working memory abilities which requires them to hold multiple items in memory in the face of distraction.

Traumatic brain injury affects individuals' EF ability in specific ways. More complex EFs are typically affected, while other abilities such as simple span memory seem relatively spared. Subtle deficits in EF observed in mTBI individuals may underlie more severe deficits often exhibited by individuals with moderate to severe TBI. Previous researchers have suggested that mild deficits on tasks that measure inhibition, reasoning ability, task switching, and working memory may underlie more severe deficits in patients with more moderate to severe TBI, such as disinhibition, flexible adjustments of behavior, and complex problem solving. These deficits will negatively impact individuals' performance in complex social, academic, and professional environments. In addition to common EF deficits, bilinguals who experience a TBI are likely to show additional deficits in language processing and language control because bilinguals rely on EF to manage or control their languages.

Neurological Impairment in Bilinguals

Minority populations, such as Hispanics experience higher rates of TBI compared to non-minority groups (Cooper, Tabaddor, & Hauser, 1993). Higher incidence of TBI among Hispanics may be related to poverty, fewer occupational and educational opportunities, unsafe residential environments, employment in physically demanding and dangerous jobs, and possibly culture-specific health behaviors (e.g., Arango-Lasprilla et al., 2007a). Further, Hispanics have a worse prognosis post injury than non-minority groups (e.g., Arango-Lasprilla et al., 2007b; Jimenez et al., 2013). This is due to a combination of factors, such as reduced access to a physician at the time of injury, lower likelihood to see a physician following an injury, reduced access to rehabilitative services, and less social support (e.g., Arango-Lasprilla et al., 2007b; Bazarian, Pope, McClung, Cheng, & Flesher, 2003).

There is little evidence investigating the cognitive changes resulting from TBI in bilinguals. Nearly all research on cognitive deficits associated with TBI is based on monolingual populations or populations in which linguistic background is not specified. Some studies have shown that cognitive decline or disorders impact language processing in bilingual populations (e.g., Gollan, Sandoval, & Salmon, 2011; Marrero, Golden, & Espe-Pfeifer, 2002).

Studies have reported language processing deficits, or aphasia, in bilinguals following a stroke. Aphasia is a language disorder, resulting from neurological damage, which affects all communication modalities. For bilinguals who experience a stroke, one or both languages may be impaired and patterns of recovery for each language can vary widely (see Lorenzen & Murray, 2008; Marrero et al., 2002, for a review). For example, both languages can be affected similarly and recover in parallel following stroke. One language may be less affected than the other and recover more quickly, regardless of language dominance. The recovery of one language can interfere with the recovery of the other language. Additionally, the ability to switch languages may also be impaired, particularly if there is a lesion in the frontal lobe (e.g., Mariën, Abutalebi, Engelborghs, & De Deyn, 2005). Individuals may be unable to switch languages, they may be able to switch languages in only one direction, or they may switch languages involuntarily (e.g., Fabbro, 2001). Thus, neurological impairment will impact a bilingual's ability to communicate in both languages and their ability to effectively control their languages.

Cognitive decline due to normal healthy aging may also impact language control and EF abilities in bilinguals. Gollan and colleagues (2011) investigated the relationship between EF and language control in healthy young Spanish-English bilinguals and healthy older Spanish-English bilinguals. Participants were asked to complete a verbal fluency task in which they named words belonging to the same semantic category (i.e., animals) or words beginning with the same letter (i.e., words beginning with *F*). Participants also completed a flanker task in which they indicated the direction of a central arrow. The central arrow was flanked by arrows pointing in the same direction (congruent) or in the opposite direction (incongruent). To complete the flanker task successfully, participants had to ignore or inhibit the distracting incongruent arrows and attend only to the central arrow. The authors found that older bilinguals were significantly slower and made more errors on the flanker task than younger bilinguals, suggesting reduced inhibition abilities. Additionally, compared to younger bilinguals, older bilinguals were more likely to make cross-language errors (e.g., producing 'pulpo' instead of 'octopus' in the animal category) during the verbal fluency task. Critically, there was a significant relationship between flanker task errors and cross-language errors in the verbal fluency task for older bilinguals. As inhibition declined in the older bilingual adults, language control abilities also declined, resulting in more cross-language errors. The authors argued that age-related declines in EF are related to declines in language control abilities.

While there are currently no studies directly investigating the impact of mTBI on bilingual EF and language control, there is evidence to suggest that neurological impairment or decline does lead to EF deficits and language control failures (e.g., Gollan et al., 2011; Lorenzen & Murray, 2008; Marrero et al., 2002). Following a TBI, bilinguals will likely experience difficulty switching between languages, translating information from one language into another, and/or greater difficulty retrieving words in one language compared to the other. These deficits will likely affect their ability to communicate effectively on daily basis. As the number of Spanish-English bilinguals continues to increase in the United States (Shin & Kominski, 2010), these individuals will become a larger part of the referral base for clinicians. The effect of brain injury on language control and other executive functions will be an increasingly important issue (Lorenzen & Murray, 2008; Marrero et al., 2002). Clinicians who assess and treat bilingual speakers need empirical evidence to guide their practice (American Speech-Language-Hearing Association, 2004).

The current study investigated how mTBI may impact performance on tasks designed to measure inhibition, task switching, simple span memory, working memory, reasoning, and language control abilities in Spanish-English bilinguals. The first experiment was designed to simulate mTBI in healthy bilingual participants. Participants completed several primary tasks with and without secondary load. If mTBI affects bilingual EF and language control, healthy bilinguals should show impaired performance when given a secondary load relative to the primary task alone. The second experiment examined the impact of mTBI on bilingual EF and language control abilities in bilinguals with a history of mild traumatic brain injury and healthy control bilinguals. If traumatic brain injury affects bilingual cognition and language control abilities, then individuals with acquired mild traumatic brain injury should show worse performance than healthy control bilinguals on EF tasks and language control tasks, but not simple span memory tasks. Including simple span memory tasks ensures that secondary load or group differences on EF tasks are not due to deficits in simple span memory.

A second aim of the present study is to examine the relationship between EF and language control. The IC model and adaptive control hypothesis both posit EF mechanisms that regulate language control in bilinguals. Individuals who have deficits in EF, either resulting from mTBI or due to the added demands of a secondary load, should show more language control deficits. It was expected that as EF abilities decline, more language control deficits will be observed.

This experiment examined which demographic factors identify a possible subset of bilinguals who are at the greater risk of language control deficits following mTBI. Determining which subset of bilinguals is at greater risk for language control deficits following mTBI will aid clinical decision making regarding further need for assessment. Bilinguals who are highly proficient across two languages should show more language control deficits following an mTBI than bilinguals who are dominant in one language. This hypothesis seems counterintuitive. However, the adaptive control hypothesis posits that bilinguals with high proficiency in both languages (i.e., balanced) bilinguals recruit EF more for language control than bilinguals who are dominant in one language (e.g., Green & Abutalebi, 2013). If balanced bilinguals acquire a mTBI which results in deficits to the critical EF mechanisms need for language control, they may be at greater risk of language control deficits following mTBI than language dominant bilinguals.

This study used eye tracking methodology to provide a possible explanation for which EF mechanisms may underlie language control deficits in bilinguals. Eye tracking is a sensitive tool that can be used to investigate EF processes. For example, eye movement data have been used to reveal inhibitory control deficits in patients with frontal lobe injuries (e.g., Munoz & Everling, 2004). During reading, eye movements are influenced by various linguistic and cognitive factors, such as word frequency, word length, part of speech, and age of acquisition (see Rayner, 1998, 2009 for a review). These factors will influence when and where readers move their eyes. For example, readers will fixate longer on words that are longer in length or are infrequent (e.g., Rayner, 1979; Rayner & Duffy, 1986). Additionally, content word (e.g., nouns, verbs, adverbs, and adjectives) are fixated more than function words (e.g., articles, conjunctions, preposition). These patterns are similar whether someone reads in their dominant language or second language (e.g., Altarriba, Kroll, Sholl, & Rayner, 1996; Gollan, Schotter, Gomez, Murillo, & Rayner, 2014). When healthy young bilinguals skip words during a reading aloud task, they will make more errors (Gollan et al., 2014). Interestingly, bilinguals may make errors in the same language as the printed text (e.g., saying ‘would’ instead of ‘should’) or in the non-target language (e.g., saying ‘hora’ when the printed word is “hour’). A paragraph reading task was used to measure language control abilities, and participants’ eye movements were recorded during reading. Bilinguals that are taxed with a secondary load during reading or bilinguals with a history of mTBI may also make more errors when not attending to the target word, similar to healthy bilinguals (e.g., Gollan et al., 2014). Alternatively, bilinguals taxed with a secondary load during reading or bilinguals with a history of mTBI may show different patterns of eye movements. If mTBI impacts inhibitory control, then these individuals may make errors despite fixating on the target word and fixating it for longer durations. This may be due to a reduced ability to inhibit the non-target language following a mTBI.

Experiment 1

Experiment 1 examined how mTBI affected performance on a range of EF and language control tasks in a group of healthy Spanish-English bilinguals using a secondary load task to simulate mTBI. Secondary load, or cognitive load, is thought limit cognitive control or attentional capacity (e.g., Lavie, 2010). When individuals have to switch between a primary task and secondary task, or when they have to maintain secondary load items in working memory, performance on the primary task is disrupted. The ability to attend to task relevant stimuli decreases and attention to distracting, task irrelevant stimuli increases (e.g., Lavie, 2005, 2010; Lavie, Hirst, de Fockert, & Viding, 2004). Additionally, secondary load may hinder the ability to encode and retrieve items from memory (e.g., Kane & Engle, 2000). In this way, secondary load is thought to mimic the decreased processing capacity observed in patients with frontal lobe injury (e.g., Lavie, 2005, 2010).

Research has shown that using a secondary load task can simulate frontal lobe deficits in healthy individuals. For example, Dunbar and Sussman (1995) investigated how a secondary load affected performance on the Wisconsin Card Sorting Task, which served as the primary task. In the Wisconsin Card Sorting Task, participants were asked to sort cards according to an undisclosed rule. For example, participants needed to sort cards based on color categories, but were not provided with the rule. Once a participant started sorting the cards, an examiner indicated whether the response was right or wrong. Some participants only completed the primary task, while others also performed a secondary task in which they heard a stream of digits and had to report the last digit when cued. Participants who performed the secondary task made significantly more errors than participants who completed the primary task alone. Further, the types of errors made were consistent with errors observed in patients with frontal lobe deficits. The authors concluded that a secondary load disrupted participants' ability to use executive function to manipulate information, which may be similar to the types of executive dysfunction observed in patients with frontal lobe damage.

Other studies have shown that participants perform worse when they are given a secondary load task paired with a primary task than when given the primary task alone (e.g., Moscovitch, 1994; Rohrer, Wixted, Salmon & Butters, 1995). For example, Rohrer et al. (1995) asked participants to perform a verbal fluency task alone or while simultaneously tapping computer keys. In the verbal fluency task, participants were given a semantic category and had to provide exemplars. The authors found that participants produced significantly fewer exemplars and produced exemplars more slowly when also doing the secondary load task. This pattern was consistent when compared with a group of individuals with frontal lobe deficits (Rohrer et al., 1995). Other studies have also shown that participants with a history of mTBI produce fewer exemplars in a verbal fluency task than healthy control participants (e.g., Henry & Crawford, 2004; Zakzankis, McDonald, & Troyer, 2011).

Mangels, Craik, Levine, Schwartz, and Struss (2002) investigated how a secondary load task affected memory for photographs. Participants were asked to study photographs for a later memory test. In the secondary load condition, participants were also asked to keep track of auditory digits while studying the photographs. The authors found that healthy individuals produced significantly more errors when also keeping track of auditory digits compared to the primary task alone. The errors patterns were consistent with errors observed in a group of mTBI individuals and suggested that the secondary load disrupted the ability to encode and retrieve items from memory (Mangels et al., 2002).

The addition of a secondary load task can simulate the response and error patterns observed in individuals with frontal lobe deficits across a variety of EF tasks. The first experiment examined how a secondary load task affected performance in a group of healthy young bilinguals. Participants were given tasks designed to measure inhibition, simple span memory, working memory, and language control abilities. For the language control measures, participants were required to rapidly switch between English and Spanish in some conditions. Participants completed these tasks either alone or with secondary load. In the secondary load task, participants completed a 1-back task with tones and/or digits. In the 1-back task, participants were asked to compare if a current tone or digit is higher or lower than the previous tone or digit. This secondary load was designed to disrupt participants' ability to use EF to manipulate information on the primary tasks. Participants should show a decline in performance when given the primary task paired with the secondary load than when given the primary task alone. For language control measures, these declines should be greater under secondary load and when participants must rapidly switch between both languages. Moreover, bilinguals have shown greater declines in performance when tasks are verbal in nature compared with nonverbal tasks (e.g., see Bialystok, Craik, Green, & Gollan, 2009 for a review). A verbal secondary load (i.e., digit 1-back) should produce greater declines in performance than a nonverbal secondary load (i.e., tone 1-back).

This experiment also investigated the relationship between performance on EF task and language control measures. Prior research conducted by Gollan and colleagues (2011) showed that as EF abilities decline, language control deficits increase. In the present study, bilinguals who perform better on measures of EF should also show fewer language control deficits.

Eye tracking measures were used to examine possible underlying mechanisms responsible for language control deficits. During a reading task, participants' eye movements were tracked. Eye movement data were used to reveal the total duration (e.g., gaze duration) on words that were produced in error. Additionally, eye tracking was used to determine where participants placed their visual attention when they produced an error or when they read target items correctly. Gaze duration and the proportion of eye fixations should differ across no load and secondary load conditions. Under conditions of no load, participants should make more errors when their eyes are not fixated on the target word or if they fixated the word for a short duration (e.g., Gollan et al., 2014). The presence of a secondary load should disrupt inhibitory control processes required for successful language control and participants should make errors despite more and longer fixations on the target word.

Lastly, this experiment examined which demographic factors are related to language control deficits. The adaptive control hypothesis assumes that balanced bilinguals recruit EF more for language control than bilinguals who are dominant in one language. It was expected that balanced bilinguals would show more language control deficits, particularly under conditions of secondary load, which taxed EF abilities.

Method

Participants. All participants were recruited from Arizona State University undergraduate classes and received partial course credit for their participation. Participants reported no history of memory, language, or neurological problems. Thirty-nine self-reported Spanish-English bilingual individuals participated the study. For the eye-tracking portion of the study, data for two participants were not included in the analysis due to equipment malfunction. A modified version of the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian, Blumenfeld, & Kaushanskaya, 2007) was used to measure self-reported language use and proficiency in the bilingual participants. Additionally, participants completed a standardized receptive vocabulary measure in English, the *Peabody Picture Vocabulary Test – 3rd Edition, (PPVT-3)*(Dunn & Dunn, 1997) and a standardized receptive vocabulary measure in Spanish, *Receptive One-Word Picture Vocabulary Test in Spanish – 4th Edition (ROWPVT-4 Spanish)*(Martin, 2012) (see Table 1 for language profiles). All participants gave informed consent and the experimental procedures were approved by the Arizona State University Human Subjects Institutional Review Board.

Stimuli. A total of 100 words were used for the operation span tasks. Fifty words were used in each operation span task (English and Spanish). All English and Spanish word lists were balanced in word length, log frequency, and concreteness. Log frequencies were calculated based on Kučera and Francis norms (1967) and the LEXESP database (Sebastián-Gallés, Martí, Cuetos, & Carreiras, 2000). To calculate concreteness, Spanish words were translated into English and the English norms for concreteness were used (Gilhooly & Logie, 1980; Pavio, Yuille, & Madigan, 1968) (see Appendix B for word lists). The symmetry span task stimuli were taken from Unsworth, et al. (2005). The flanker task stimuli were adapted from Emmorey, Luk, Pyers, & Bialystok (2008). Paragraphs for the reading aloud task were taken from Gollan et al. (2014). Stimuli for the confrontational naming task were photographs of real world objects taken from Brady, Konkle, Alvarez, and Oliva (2008), Brady, Konkle, Alvarez, and Oliva (2013), and Konkle, Brady, Alvarez, and Oliva (2010). A total of 126 images were resized, maintaining original proportions, to 3.8° × 3.8° in visual angle. The common label or name of each item was translated into Spanish. The log frequency for each label was calculated based on Kučera and Francis norms and the LEXESP database. English and Spanish labels were balanced in word length and log frequency (see Appendix C for images). Secondary load verbal stimuli were digits 1-9, recorded by a native English speaker, and digitized at a 44100 Hz sampling rate. Nonverbal stimuli were pure tones with the following frequencies: 250Hz, 500Hz, 750Hz, 1000Hz, and 2000Hz sampled at 44100 Hz.[1]

Procedure. The experiment was presented on PC-compatible computers using E-prime 1.2, an experimental operating system (Schneider, Eschman, & Zuccolotto, 2002). Instructions and experimental stimuli were presented in black, Arial font against a white background. The experimenter also read the instructions aloud. The experiment consisted of two sessions, one 30 minute session and a 90 minute session. All tasks were presented in random order. The reading aloud task was programmed in Experiment Builder software and paragraphs were presented in 22 point font using a Dell Optiplex 755 PC. The display was a 21-inch NEC FE2111SB CRT monitor (20 inch viewable),

[1]Pure tone discrimination was tested in a sample of six participants. Participants were able to discriminate differences between all pairs of pure tones with 92% or higher accuracy.

with resolution set to 1024 × 768 and a 60 Hz refresh rate. Eye-movements were recorded using a desktop-mounted Eyelink 1000 eye tracker (SR Research Ltd., Mississauga, Ontario, Canada). Temporal resolution was set to 1000 Hz, and spatial resolution was 0.01° in visual angle. Participants were initially calibrated to ensure accurate tracking and used a chin rest during all reading trials. The chin rest was positioned 60 cm from the monitor. Periodic drift correction and recalibrations were used to ensure accurate recording of gaze position.[2]

Standardized Assessments. The *Peabody Picture Vocabulary Test (3rd Edition) (PPVT-III)* (Dunn & Dunn, 1997) is a standardized measure of receptive vocabulary in English. The assessment consists of a series of plates, each containing four black and white images, with a number below each image. A vocabulary word was presented to participants and they were asked to identify which of the images corresponded to the given word by entering the number paired with the image. The starting point of the assessment is determined by the age of the participant. A basal score is determined by 11 correct responses out of 12 within a block. A ceiling is reached when the participant makes either eight errors out of 12 items, within a block, or reaches the end of the assessment. The standard score was determined by converting the raw score into a standard score using the participant's age.

The *Receptive One Word Picture Vocabulary Test – Spanish (4th Edition) (ROWPVT-4 Spanish)* (Martin, 2012) is a standardized measure of receptive vocabulary in Spanish. The assessment consists of a plates, each containing four colored images

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[2] Prior to data analysis, eye movement data were pre-processed. First, an experimenter watched video recordings of the eye movements, paired with the digital audio recordings of each participant reading the paragraphs. Eye fixations were moved, vertically until they fell in the nearest interest area for a word.

with a number below each image. A vocabulary word was presented to participants and the participants were asked to identify which of the images corresponded to the given word by entering the number paired with the image. The starting point of the assessment was determined by the age of the participant. A basal score is determined by eight consecutive correct responses. A ceiling is reached when the participant makes either four consecutive errors, or reaches the end of the assessment. The standard score was determined by converting the raw score into a standard score using the participant's age.

Raven's Advanced Progressive Matrices (RAPM) (Raven, Raven, & Court, 1998) is a measure of general fluid intelligence or non-verbal reasoning. The abbreviated version contains 18 problems that progressively increase in difficulty. Participants were shown a display of 3 X 3 matrices of geometric patterns with the bottom right pattern missing. Additionally participants were shown eight pieces and were asked to select which of the eight pieces correctly completed the pattern in the display. Participants had 10 minutes to complete as many items as possible.[3]

Experimental Tasks. In the forward digit span task, participants were presented digits, one at a time, for 1000 ms each while simultaneously keeping track of a digit or tone. Participants heard a digit or tone for 1000 ms, then were presented with sets of three to seven digits. At a recall prompt, participants were asked to type the digits in the order of presentation. Participants were told to type an X if they forgot a digit in the sequence. After entering the digits, participants heard another digit or tone and were asked to report if it was higher or lower than the previous digit or tone (1-back) (see

[3] *Raven's Advanced Progressive Matrices* was included to control for possible differences in IQ between Experiments 1 and 2. The mean score was 8.03 (*SD* = 3.48).

Figure 1). Tone verification was based on the pitch. Participants had a maximum of 4000 ms to complete the digit or tone verification. Participants completed three practice sets, one in which they were only asked to recall digits, one in which they only practiced the 1-back task, and one set in which the primary digit task and secondary 1-back task alternated. In the experimental portion, there were two trials at each span length and span lengths were presented in progressive order. One-third of participants received the standard forward digit span task, with no secondary load. One-third of participants received the task paired with auditory digits (verbal load). One-third of participants received task paired with tones (nonverbal load). The procedure for the backward digit span task was identical to the forward digit span task except that participants were asked to type digits in reverse order.

In the English and Spanish operation span tasks, participants were shown a two-step math equation to verify and a word to remember while simultaneously keeping track of a digit or tone. Participants heard a digit or tone for 1000 ms each, then were presented sets of three to seven equation-word pairs. They responded to the math equations by pressing keys marked YES and NO (the P and Q keys on a standard keyboard, respectively) and received feedback after each response. Following feedback, a memory word was presented for 1000 ms. At a recall prompt, participants were asked to type the words in the order of presentation. Participants were told to type an X if they forgot a word in the sequence. Then, participants heard another digit or tone and were asked to report if it was higher or lower than the previous digit or tone (see Figure 2). Participants had a maximum of 4000 ms to complete the digit or tone verification. Sets contained three to seven equation-word pairs with two trials at each span length.

Participants completed two practice trials, containing four equation-word pairs prior to the experimental portion of the task. Span lengths were presented in random order. The English operation span task used English words and the Spanish operation span task used Spanish words. One-third of participants received the standard operation span task, with no secondary load. One-third of participants received the task paired with auditory digits (verbal load). One-third of participants received task paired with tones (nonverbal load).

The symmetry span task is a measure of nonverbal working memory (Unsworth, et al., 2005). Participants were shown black and white images and asked to report whether the images were symmetrical around a vertical axis. Symmetry images were shown for 4000 ms or until a response was entered. To indicate that a picture was symmetrical, participants clicked on the image with a computer mouse, which triggered a YES and NO option to appear. After entering a response, participants were shown a 4 x 4 matrix with one square shaded red for 1000 ms. Following the matrix, another black and white image appeared for symmetry judgment. At a recall prompt, participants were asked to recall the order of the red squares by clicking squares on a blank grid with the computer mouse. Participants were instructed to click a box marked BLANK if they forgot the location of a red square. They received feedback on their performance after each set. Sets contained two to six symmetry-memory matrices pairs with two trials at each span length and span lengths were presented in random order.[4]

The flanker task was adapted from Emmorey et al. (2008) and Bunge, Dudukovic, Thomason, Vaidya, and Gabrielli (2002) and contained three conditions: control, go/no-

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[4] The symmetry span task was included to control for possible differences in WM between Experiments 1 and 2 and to allow for cross task comparisons in Experiment 1. Overall participants recalled 20.49 squares in the correct order (*SD* = 7.32).

go, and conflict. Participants were asked to indicate the direction of the red chevron arrow on all trials. In the control condition, participants indicated the direction, either left or right (the N and M keys on a standard keyboard, respectively) of a single arrow. In the go/no-go condition, participants indicated the direction of the arrow in the go trials and were asked to withhold a response in the no-go trials. The go trials presented a central arrow flanked by four diamonds and the no-go trials presented the arrow flanked by four Xs. The conflict condition consisted of congruent and incongruent trials. In the congruent trials, the red arrow was flanked by four gray arrows pointing in the same direction, or in the opposite direction for the incongruent trials. The secondary load task and primary task alternated trial by trial. Participants heard a tone or a digit for 1000 ms, then were presented an arrow and had to indicate the direction, then they heard another tone or digit and were asked to report if the present tone or digit was higher or lower than the one that preceded the arrow (see Figure 3). Arrow trials were presented for 3000 ms or until a response was entered. Participants had a maximum of 4000 ms to complete the digit or tone verification. In the practice session, participants received 12 trials of each condition (control, go/no-go, and conflict) and twelve independent trials of the 1-back task, six tones and six auditory digits. Then participants were given 24 practice trials with the primary and secondary task alternating, 12 tone and 12 auditory digit. Participants received feedback on their overall performance after each block. In the experimental portion, each condition was paired with each load type, for a total of nine experimental blocks with 32 trials per block. In half of the trials, the central arrow pointed to the right.

In the confrontational naming task, participants were presented photographs of common items and were asked to name them aloud in either English or Spanish. A capital letter 'E' or 'S' appeared above each image to cue the participants if they should name the image in English or Spanish. Participants named items in three different conditions: English only, Spanish only, and Mixed language in which English and Spanish were intermixed. Two word lists were generated allowing for items to be counterbalanced across languages. Spanish words for half of the participants were shown as English words for the other half of the participants (and vice versa). Prior to each image, participants heard a either tone or digit for 1000 ms, then a buzzer sound for 500 ms to signal the beginning of the naming trial. Then, an image appeared on the screen for 5000 ms. Participants were instructed to respond as quickly as possible and provide the most common label for each time. They were instructed to say "I don't know" if they did not know the label for an item in a particular language. Then, participants heard another tone or digit and were asked to report if the present tone or digit was higher or lower than the one that preceded the image (see Figure 4). In the practice session, participants received 12 trials, four naming trials paired with each load type (no load, digits, or tones). The experimental session contained a total 126 trials. Each language condition was paired with each load type, for a total of nine experimental blocks with 14 trials per block. An experimenter recorded each session using a digital recording device.

For the reading aloud task, participants read paragraphs aloud while simultaneously keeping track of auditory digits or tones. Paragraphs were presented in four different conditions: English only, Spanish only, Mixed language with English word order, and Mixed language with Spanish word order. Participants heard an auditory digit or tone for 1000 ms, then a buzzer sound to signal the onset of a paragraph. Then, they were presented a paragraph which they read aloud followed by another auditory digit or tone. They were asked to report if the current auditory digit or tone was higher or lower than the one that preceded the paragraph. Participants had a maximum of 4000 ms to complete the digit or tone verification. Prior to a secondary load manipulation, participants received 4 practice trials of that load type, with the exception of the no load condition. Paragraphs were rotated across conditions so that each participant reads three paragraphs paired with each load type, for a total of 12 paragraphs. The order of the conditions was randomized. Participants were asked to read the paragraphs at a comfortable pace without time restrictions. An experimenter recorded each session using a digital recording device.

Task Scoring. Complex WM tasks and simple span tasks were scored using a proportion correct scoring method (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005; Unsworth & Engle, 2007). For each item (e.g., digit, word, or red square) that was recalled in the correct order, a point was given. English and Spanish operation span task responses were scored for six types of errors: omissions, transpositions, partially recalled words, phonemic errors, semantic errors, and perseveration errors. *Omission errors* reflect words that were not recalled. A *transposition error* occurred when a word was recalled, but in the wrong order. A *partial recall* occurred when part of the word was recalled, but it was unclear if the participant knew the target word (e.g., “dri” for drink). A *phonemic error* occurred when a word was replaced with a phonologically similar word (e.g., “deal” for dear). A *semantic error* occurred when a word was replaced with a semantically similar word (e.g., “bench” for seat). A *perseveration error* occurred when participants repeated a word from a previous set. Participants were given credit for misspelled words if no other possible word could result from the provided response (e.g., “wieght” was considered a correct response for “weight”).

Both language control tasks were also scored for errors. The confrontational naming task was scored for cross language intrusions. A *cross-language intrusion* occurred when participants produced a word in the non-target language (e.g., saying ‘dog’ when cued for the Spanish word ‘perro’). In the reading aloud task, four types of errors were recorded: cross language intrusions, accent errors, within language errors, and omission errors. A *cross-language intrusion* occurred when participants produced a word in the non-target language (e.g., saying ‘él’ when the printed word was ‘he’). An *accent error* occurred when participants produced target word, but with the pronunciation of the non-target language. *Within language errors* were semantic or phonological errors in the same language as the target. *Omission errors* occurred when participants skipped a printed word.[5] Two separate eye movement measures were used in the current study, gaze duration (or dwell time) and proportion of fixations. Gaze duration reflects the total summed of fixations made on a word.[6] Proportion of fixations reflect whether a word was skipped during reading. A word was counted as “fixated” if there was a fixation on the word while the participant read the word aloud. Gaze duration and proportion of

[5] For the total errors, 25% of the data were scored by two independent raters. The interrater correlations were high (Cross Language Intrusions ($r(10) = .942$, $p<.001$); Accent Errors ($r(10) = .897$, $p<.001$); Within Language Errors ($r(10) = .986$, $p<.001$); Omission Errors ($r(10) = .933$, $p<.001$)).

[6] Gaze duration (or dwell time) was used in place of first fixation or single fixation duration. All three measures yield similar effects (e.g., Rayner & Liversedge, 2011). Additionally, participants frequently made several fixations on a single word, making it difficult to detect the exact fixation that corresponded to an error.

fixations were also recorded for control words. Control words were words that were read correctly by participants and were selected based on the following criteria: were in the same paragraph as error, same target language as error, same part of speech as error, and approximately the same length as error.[7]

Results

For the operation span tasks and simple span tasks, a 3(Load Type: No Load, Verbal Load, Nonverbal Load) between-subjects analysis of variance (ANOVA) was used to analyze total items recalled (i.e., digit or words), and equation accuracy. Operation span task errors were analyzed using a 3(Load Type: No Load, Verbal Load, Nonverbal Load) × 6(Error Type: Omissions, Transpositions, Partially Recall, Phonemic Errors, Semantic Errors, or Perseverations) mixed ANOVA. For all post-hoc analyses for all tasks, a Bonferroni adjusted alpha was used for multiple simultaneous comparisons.

Simple Span Tasks. The main effect of Load Type was not significant for items recalled in either the Forward Digit Span task ($F(2, 37) = 1.99$, $p=.151$) or the Backward Digit Span task ($F<1$). Overall, participants recalled more digits in the Forward than the Backward Digit Span task ($M = 42.89$ vs. $M = 37.21$) ($t(37) = 6.16$, $p<.001$) (see Table 2).

[7] Log frequencies for error words and control words were calculated based on Kučera and Francis norms (1967) and the LEXESP database (Sebastián-Gallés et al., 2000). Error words were 4.59 letters in length ($SD = 2.43$) and control words were 4.42 letters in length ($SD = 2.11$). Control words were significantly shorter than Error words ($t(622) = 2.68$, $p=.007$), likely due to a large sample ($N = 623$). However, Error words and Control words differed by 0.17 letters, with small effect size ($d=.07$). The average log frequency for Error words was 2.80 ($SD = 1.28$) and for Control words 2.60 ($SD = 1.47$). Again, there was a significant difference in log frequency between Error and Control words ($t(622) = 4.21$, $p<.001$), but the effect size was small ($d=.15$).

Operation Span Tasks. For the English operation span task, the main effect of Load Type on items recalled was significant ($F(2, 37) = 4.05$, p=.026, $\eta_p^2 = .188$). Participants in the Nonverbal Load condition recalled marginally more items than either the No Load condition ($t(24) = 2.48$, p=.021) or the Verbal Load condition ($t(22) = 2.43$, p=.024). The main effect of Load Type was not significant for equation accuracy (F<1) (see Table 2). For the error analyses, the main effect of Load Type was marginally significant ($F(2, 35) = 2.91$, p=.068, $\eta_p^2 = .143$) which reflects participants' making marginally fewer errors in the Nonverbal Load condition than the No Load condition ($t(24) = 2.31$, p=.030) or the Verbal Load condition ($t(22) = 2.16$, p=.042). The main effect of Error Type was also significant ($F(5, 180) = 91.05$, p<.001, $\eta_p^2 = .722$).[8] The Load Type × Error Type interaction was significant ($F(2, 35) = 2.10$, p=.027, $\eta_p^2 = .107$). Participants made marginally fewer Partial Recall Errors and Perseveration Errors in the Nonverbal Load condition compared to the No Load condition ($t(24) = 2.34$, p=.028; $t(24) = 2.32$, p=.029, respectively) (see Table 3).

For the Spanish operation span task, the main effect of Load Type was not significant for either items recalled or equation accuracy (both *Fs*<1). For the error analyses, the main effect of Load Type was not significant (F<1). The main effect of Error Type was significant ($F(5, 180) = 174.99$, p<.001, $\eta_p^2 = .829$).[9] The Load Type × Error Type interaction was not significant (F<1).

[8] Participants made more Omission Errors than Transmission Errors ($t(37) = 9.09$, p<.001), Partial Recall Errors ($t(37) = 9.70$, p<.001), Phonemic Errors ($t(37) = 9.22$, p<.001), Semantic Errors ($t(37) = 9.84$, p<.001), and Perseveration Errors ($t(37) = 9.87$, p<.001). Additionally, participants made more Transposition Errors than Partial Recall Errors ($t(37) = 4.44$, p<.001), Phonemic Errors ($t(37) = 3.53$, p=.001), Semantic Errors ($t(37) = 5.56$, p<.001), and Perseveration Errors ($t(37) = 3.96$, p<.001).
[9] Participants made more Omission Errors than Transmission Errors ($t(37) = 13.36$, p<.001), Partial Recall Errors ($t(37) = 14.04$, p<.001), Phonemic Errors ($t(37) = 13.79$, p<.001), Semantic Errors ($t(37) = 14.61$, p<.001), and Perseveration Errors ($t(37) = 14.71$, p<.001). Participants also made more Transposition

Flanker Task. Correct RTs and accuracy were analyzed using a 3(Load Type: No Load, Verbal Load, Nonverbal Load) × 3(Condition: Control, Go/no-go, or Conflict) repeated measures ANOVA. A conflict effect was calculated by taking the difference in RT and accuracy for incongruent trials compared to congruent trials within the conflict block. The conflict effect was analyzed using 3(Load Type: No Load, Verbal Load, Nonverbal Load) repeated measures ANOVA.

The main effect of Load Type was significant ($F(2, 74) = 44.76$, $p<.001$, $\eta_p^2 = .547$). Response times were faster in the No Load condition compared to both the Verbal Load ($t(37) = 4.76$, $p<.001$) and Nonverbal Load conditions ($t(38) = 8.97$, $p<.001$). The main effect of Condition on RTs was significant ($F(2, 74) = 325.23$, $p<.001$, $\eta_p^2 = .898$). Responses in the Go/no-go condition were faster than the Control ($t(37) = 18.70$, $p<.001$) and Conflict conditions ($t(38) = 21.69$, $p<.001$). Additionally, RTs in the Control condition were faster than in the Conflict condition ($t(37) = 4.76$, $p<.001$). The Condition × Load Type interaction was significant ($F(4, 148) = 3.19$, $p=.015$, $\eta_p^2 = .079$). Within the Control condition, responses were faster for No Load trials compared to Verbal Load trials ($t(37) = 5.52$, $p<.001$) and Nonverbal Load trials ($t(38) = 6.69$, $p<.001$), with no significant difference between the two load conditions. Similarly, within the Conflict condition, RTs were faster for No Load trials compared to Verbal Load trials ($t(38) = 5.11$, $p<.001$) and Nonverbal Load trials ($t(38) = 6.84$, $p<.001$), with no significant difference between Verbal Load and Nonverbal Load trials. For the Go/no-go condition, RTs were faster for No Load trials compared to Verbal Load trials

Errors than Partial Recall Errors ($t(37) = 6.29$, $p<.001$), Phonemic Errors ($t(37) = 4.50$, $p=.001$), Semantic Errors ($t(37) = 7.72$, $p<.001$), and Perseveration Errors ($t(37) = 7.91$, $p<.001$).

($t(38) = 4.53$, $p<.001$) and Nonverbal Load trials ($t(38) = 6.84$, $p<.001$). In contrast to the other two conditions, RTs to Verbal trials were marginally faster than Nonverbal trials ($t(38) = 2.30$, $p=.027$) (see Figure 5 and Table A1).

For accuracy, neither the main effect of Condition nor Load Type were significant (both *F*s <1). The Condition × Load Type interaction was not significant ($F(4, 152) = 1.08$, $p = .370$).

For the conflict effect, the main effect of Load Type was marginally significant on RTs ($F(2, 76) = 2.40$, $p=.098$, $\eta_p^2 = .059$). Interestingly, participants had marginally smaller a conflict effect in Nonverbal Load condition relative to the No Load condition ($t(38) = 2.35$, $p=.024$). No other post-hoc comparisons were significant. The main effect of Load Type on the conflict effect for accuracy was not significant ($F<1$).

Confrontational Naming Task. Correct RTs, accuracy, and cross language intrusions were analyzed using a 3(Load Type: No Load, Verbal Load, Nonverbal Load) × 2(Language: English or Spanish) × 2(Mixing: Single Language or Mixed Language) repeated measures ANOVA.

For the RTs, the main effect of Load Type was significant ($F(2, 74) = 30.62$, $p<.001$, $\eta_p^2 = .453$). Response times were faster in the No Load condition than the Verbal Load condition ($t(37) = 6.29$, $p<.001$) and the Nonverbal Load condition ($t(37) = 6.80$, $p<.001$), with no difference between the two load conditions. The main effect of Language was significant ($F(1, 37) = 17.92$, $p<.001$, $\eta_p^2 = .326$). Participants were faster at naming English items than Spanish items. The main effect of Mixing was also significant ($F(1, 37) = 75.25$, $p<.001$, $\eta_p^2 = .680$). Response times were faster in the

Single Language condition than the Mixed Language condition. No interactions were significant (all F's <1) (see Figure 6).

The main effect of Load Type was marginally significant for accuracy ($F(2, 76) = 2.79$, $p=.068$, $\eta_p^2 = .068$). Participants were more accurate in the Verbal Load condition compared with both No Load and Nonverbal Load conditions; however, no post-hoc comparisons were significant (all $p_s>.05$). The main effect of Language was significant ($F(1, 38) = 51.24$, $p<.001$, $\eta_p^2 = .574$). Participants were more accurate at naming English items than Spanish items. The main effect of Mixing was also significant ($F(1, 38) = 22.20$, $p<.001$, $\eta_p^2 = .369$). Responses in the Single Language condition were more accurate than the Mixed Language condition. The Load Type × Language interaction was significant ($F(2, 76) = 3.31$, $p=.042$, $\eta_p^2 = .080$). The Load Type × Mixing interaction was also significant ($F(2, 76) = 8.23$, $p=.001$, $\eta_p^2 = .178$). The Language × Mixing interaction was not significant ($F(2, 76) = 2.50$, $p=.122$). The two-way interactions were qualified by a significant Load Type × Language × Mixing interaction ($F(2, 76) = 6.38$, $p=.003$, $\eta_p^2 = .144$). The difference between Single and Mixed Language conditions was not significantly different across Load Types for English items (all $p_s>.017$). However, for Spanish items, responses were more accurate for the Single Language than Mixed Language condition for both No Load ($t(38) = 3.24$, $p=.002$) and Nonverbal Load conditions ($t(38) = 4.74$, $p<.001$) (see Figure 7).

For cross language intrusions, the main effect of Load Type ($F(2, 76) = 2.05$, $p=.136$), the main effect of Language ($F<1$), and the main effect of Mixing ($F<1$) were not significant. The Load Type × Mixing interaction was significant ($F(2, 76) = 3.53$,

p=.034, η_p^2 = .085) (see figure A1); however, no post-hoc comparisons were significant (all p_s>.05). No other interactions were significant (all p_s>.10).

Reading Aloud Task. Total errors were analyzed using a 3(Load Type: No Load, Verbal Load, Nonverbal Load) × 4(Error Type: Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors) repeated measures ANOVA. Gaze duration and proportion of fixations were analyzed 3(Load Type: No Load, Verbal Load, Nonverbal Load) × 2(Word Type: Error or Control) repeated measures ANOVA (see Table 4 for a summary of errors).[10,11]

For the error analyses, the main effect of Load Type was not significant (F(2, 72) = 1.20, p=.307). The main effect of Error Type was significant (F(3, 108) = 25.41, p<.001, η_p^2 = .414). Participants made fewer Accent Errors than Cross Language Intrusions (t(36) = 8.38, p<.001), Within Language Errors(t(36) = 7.13, p<.001), and Omission Errors (t(36) = 5.40, p<.001). Additionally, participants made fewer Omission Errors than Within Language Errors (t(36) = 3.54, p<.001). The Load Type × Error Type interaction was not significant (F(6, 216) = 1.31, p=.255) (see Figure 8).

[10] The total errors were also analyzed using a 3(Load Type: No Load, Verbal Load, or Nonverbal Load) × 2(Target Language: English or Spanish) × 4(Error Type: Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors) repeated measures ANOVA. The main effect of Load Type was not significant (F(2, 72) = 1.12, p=.332). The main effect of Language was significant (F(1, 36) = 5.23, p=.028, η_p^2 = .127). The main effect of Error Type was significant (F(3, 108) = 24.59, p<.001, η_p^2 = .406). The Language × Error Type interaction was significant (F(3, 108) = 7.96, p<.001, η_p^2 = .181). The Load Type × Language interaction was marginally significant (F(2, 72) = 2.77, p=.070, η_p^2 = .071). No other interactions were significant (all p_s>.05) (see Figure A2).

[11] The total errors were also analyzed using a 3(Load Type: No Load, Verbal Load, or Nonverbal Load) × 2(Mixing: Single or Mixed) × 4(Error Type: Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors) repeated measures ANOVA. The main effect of Load Type was not significant (F(2, 72) = 1.14, p=.327). The main effect of Mixing was significant (F(1, 36) = 54.10, p<.001, η_p^2 = .600). The main effect of Error Type was significant (F(3, 108) = 24.10, p<.001, η_p^2 = .401). The Mixing × Error Type interaction was significant (F(1, 36) = 46.97, p<.001, η_p^2 = .566). No other interactions were significant (all p_s>.05) (see Figure A3).

For gaze duration, the main effect of Load Type was not significant (F<1); however, the main effect of Word Type was significant ($F(1, 31) = 17.43$, $p<.001$, $\eta_p^2 = .360$). Participants had longer gaze durations on Error words than Control Words. The Load Type × Word Type interaction was not significant ($F(2, 62) = 1.52$, $p=.226$) (see Figure 9).

For the proportion of fixations, the main effect of Load Type was not significant (F<1); however, the main effect of Word Type was significant ($F(1, 32) = 61.50$, $p<.001$, $\eta_p^2 = .360$). Participants made more fixations on Control words than Error Words. The Load Type × Word Type interaction was not significant ($F(2, 64) = 1.01$, $p=.371$) (see Figure 10).

Secondary Load. Participants were more accurate at comparing digits than tones ($t(6) = 5.73$, $p=.001$) (see Table 5). The mean accuracy for the 1-back digit or Verbal Load was 90% compared with 85% for 1-back tone or Nonverbal Load.

Comparisons across Tasks. Simple linear regressions were conducted to examine the relationship between EF measures and language control errors. Neither the symmetry span task nor any flanker condition predicted the total number of cross language intrusions in the confrontational naming task or Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors in the reading aloud task.

Demographic Predictors. Simple linear regressions were conducted to examine the relationship between demographic factors and language control errors. Self-reported proficiency measures and vocabulary in English and Spanish (see Table 1) were used to predict the total number of cross language intrusions in the confrontational naming task.

Additionally, demographic variables and vocabulary scores were used to predict the total number of Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors on the reading aloud task. Following a Bonferroni correction, only self-rated proficiency for understanding Spanish marginally predicted Omission Errors (β = .396, $t(36)=2.55$, $p=.015$). As proficiency for understanding Spanish increased, the number of Omission Errors increased.

Discussion

The purpose of the first experiment was to examine how simulated mTBI, using a secondary load task, impacted EF and language control in a group of healthy Spanish-English bilinguals. Two types of secondary load were used, verbal and nonverbal. It was expected that the verbal secondary load would result in greater declines in performance than the nonverbal secondary load. Evidence has shown that bilinguals exhibit greater disadvantages for verbal tasks than nonverbal tasks (e.g., Bialystok et al., 2009). Overall, these two types of load did not differ in their effect on the primary task, contrary to hypotheses. Participants were more accurate in the verbal 1-back than the nonverbal 1-back task, suggesting that the nonverbal load was a more difficult secondary task than the verbal load. This added difficulty may have outweighed a possible verbal disadvantage.

It was hypothesized that a secondary load would result in declines in performance relative conditions without the secondary load. The effect of secondary load on EF tasks and language control tasks was inconsistent. For simple span memory tasks, such the forward and backward digit span task, load did not affect performance. This result was not surprising. Individuals with acquired mTBI typically do not perform worse than healthy controls on simple span memory tasks (e.g., Anderson & Knight, 2010; Ozen et al., 2010). The fact that secondary load did not result in worse performance on these tasks is consistent with the hypotheses and prior evidence.

Secondary load had no effect on operation span task performance, a measure of working memory. Prior studies have shown that individuals with mTBI perform worse than healthy controls on working memory tasks (e.g., Dean & Sterr, 2013), like the operation span task (e.g., Terry et al., 2012). It was expected that secondary load would result in overall worse performance on these tasks. However, secondary load did not result in declines in the total words recalled, accuracy, or the number of errors made for either the English or Spanish version of the operation span task. Interestingly, the nonverbal secondary load improved performance on the English version of the operation span task. The between-subjects manipulation may explain why we did not observe secondary load effects on working memory performance. This manipulation resulted in small sample sizes in each group (e.g., no load, verbal load, nonverbal load). The between-subjects design may also explain why participants recalled more words and made fewer errors in the nonverbal condition. It may be possible that the small group of participants that completed the English operation span task paired with the nonverbal load had higher working memory ability than the participants that completed the task with no load or verbal load. A larger sample size or a within-subjects manipulation may reveal declines in performance in the presence of a secondary load.

The effect of a secondary load task on flanker task performance was mixed. The secondary load did not affect overall accuracy on the flanker task, in contrast with Swick et al. (2012) who found that individuals with mTBI were less accurate that healthy controls. The participants in the present study had high accuracy across all conditions of the flanker task, which may explain differences between the present study and the findings of Swick et al. (2012). A second possible explanation for the lack of secondary load effects on accuracy in this study may be related to differences in our task compared with the task used by Swick et al. Swick and colleagues asked participants to identify a central letter except when the letter was flanked by X's. In the present study, participants reported the direction of central arrow. Identifying a central letter may be more difficult than the direction of an arrow, which would result in greater error rates, and potentially greater differences between healthy controls and individuals with mTBI. However, the addition of a secondary load resulted in slower response times across control, conflict, and go/no-go conditions. These findings are somewhat consistent with Dimoska-Di Marco et al. (2011) who found that individuals with a history of TBI exhibit slower response times in a go/no-go task than healthy controls. Interestingly, secondary load resulted in slower response times in the go/no-go condition. Typically, individuals with acquired TBI show symptoms consistent with disinhibition or impulsivity, particularly individuals with more moderate to severe TBI (e.g., Kim, 2002; Ylvysaker et al., 2005). If TBI leads to disinhibition or impulsivity, one would expect faster response times and more errors in the go/no-go condition. For individuals with mTBI or simulated mTBI, inhibitory abilities may be affected differently. The presence of secondary load may impair individuals' ability to rapidly switch between the rules required to perform the task (i.e., 'enter a response' to 'do not enter a response'), resulting in slower response times. Thus, secondary load may impact flexibility in decision making in the go/no-go condition.

For the confrontational naming task, the secondary load tasks resulted in slower response times, across both English and Spanish. This suggests that secondary load may result in slower ability to retrieve words in both languages without selective impairment in one language compared to the other. Secondary load did not significantly affect overall accuracy nor did it increase the number of cross language intrusions, contrary to hypotheses. It may be possible that a naming task is not sufficiently taxing on language control abilities, even when paired with a secondary load, to cause many cross language errors in healthy bilinguals.

For the reading aloud task, it was expected that secondary load may disrupt inhibitory control processes during reading resulting in more language control errors, longer gaze durations, and proportionally more fixations on error words. Contrary to hypotheses, secondary load did not affect the number of overall errors including language control errors, such as cross language intrusions and accent errors. Secondary load did not significantly affect gaze duration or the proportion of fixations on either words that were erred or control words. It is likely that the secondary load task was not sufficiently difficult to impact language control during reading. Participants were required to hold a tone or digit in memory while they read a paragraph. However, they were not required to enter any responses during paragraph reading. It may be possible to elicit more language control errors during the reading aloud task if a more difficult or taxing secondary load task is used. The nonverbal load increased the proportion of fixations for both error and control words compared to the no load condition. The increase in fixations was not significant, but it does suggest that the nonverbal load was a more difficult secondary task. Using a more difficult secondary task will likely disrupt inhibitory control processes and result in significantly more fixations on error words. Oddly, secondary load seemed to decrease gaze durations on errors words. Although this decrease was not significant, it is not clear why secondary load was associated with decreased gaze duration on error words. Participants did show overall longer gaze durations on error words compared to control words, suggesting that they may have been less familiar with those words.

The second aim of this experiment was to examine the relationship between performance on EF measures and language control. It was hypothesized that better performance on measures of EF would be related to fewer language control deficits. This hypothesis was not supported. Working memory, as measured by the symmetry span task, did not predict language control errors on either the confrontational naming task or the reading aloud task. Additionally, performance on the flanker task failed to predict language control errors. This finding is in contrast to Gollan et al. (2011) who found a relationship between flanker task performance and language control errors in healthy older bilingual adults. On average, participants made fewer than three cross language intrusions on either language control task, and less than one accent error on the reading aloud task. This may explain the nonsignificant relationship between EF and language control deficits. It may be possible to observe a significant relationship between EF performance and language control errors with an increased number of errors. A more difficult secondary load task should increase these errors.

Lastly, this experiment examined which demographic factors are related to language control errors. No language proficiency measures predicted language control errors on either the confrontational naming or the reading aloud task. Again, the nonsignificant relationship between demographic variables and language control errors may be related to the small number of errors made in the language control tasks.

The few language control errors made by the bilingual participants, even under secondary load, underscores the efficiency of bilingual language control mechanisms. Despite rapid switching between two languages, bilinguals are able to control their language production with minimal interference from the non-target language.

The results of the first experiment suggest that a secondary load task designed to simulate mTBI impacts some EFs in ways that are analogous to mTBI. In the presence of a secondary load, performance on the flanker task declined. This suggests that a secondary load task does disrupt certain inhibitory control processes. The slower response times observed in the secondary load conditions were consistent with patterns observed in a mTBI population (e.g., Dimoska-Di Marco et al., 2011). There was no consistent effect of secondary load on other tasks. It may be possible that the secondary load task was not sufficiently difficult, particularly in the reading aloud task, to simulate the predicted increase in language control errors. However, it may also be the case that bilinguals with a history of mTBI do not necessarily perform differently than healthy bilingual controls on our set of EF and language control tasks. To address this issue, it is necessary to compare performance between a group of bilinguals with a history of mTBI and healthy bilingual controls. Experiment 2 examined the impact of mTBI on EF and language control in a group of Spanish-English bilinguals who reported a history of concussions or mTBI.

Experiment 2

The second experiment investigated the impact of mTBI on EF and language control in Spanish-English bilinguals who reported a history of mTBI and a group of healthy bilingual controls. Bilingual individuals recruit EF processes to manage cross-language conflict, but no studies have examined the impact of mTBI on bilingual EF and language control. Research has shown that bilinguals exhibit language control deficits as a result of cognitive decline due to healthy aging or following stroke (e.g., Gollan et al., 2011; Lorenzen & Murray, 2008; Marrero et al., 2002). If a bilingual acquires a mTBI, they are likely to show additional deficits in EF and language control.

The second experiment had several aims. First, we investigated which EF measures and standardized assessments were sensitive to mTBI in bilinguals. Assessments and tasks that are presently sensitive to mTBI have not yet been tested on a sample of bilinguals, so it is not known if these same measures will be sensitive to mTBI in bilingual populations. Based on previous evidence, it was expected that bilinguals with mTBI would show worse performance than healthy bilingual controls on measures of EF, such as the *Functional Assessment of Verbal Reasoning and Executive Strategies (FAVRES)*), working memory tasks, inhibition tasks, and a switching task (e.g., Caeyenberghs et al., 2014; Dimoska-Di Marco et al., 2011; MacDonald & Johnson, 2005; Terry et al., 2012). They should perform similarly on tasks that measure simple span memory, such as digit span tasks and the Corsi blocks task, a nonverbal simple span measure (e.g., Anderson & Knight, 2010; Ozen et al., 2010).

This experiment also examined whether bilinguals with a history of mTBI experience more language control deficits than healthy control bilinguals. It was expected that bilinguals with a history of mTBI will make more language control errors than healthy bilingual controls, especially when required to switch between languages. Additionally, we examined whether these deficits were related to specific EF abilities. Regardless of mTBI status, bilinguals who demonstrate better performance on the EF measures should show fewer language control errors. This is due to a greater ability to regulate cross-language conflict (e.g., Gollan et al., 2011).

This experiment also tested which subset of bilinguals with mTBI may be at greater risk for language control difficulties following a mTBI based on demographic information. Bilinguals who are highly proficient, or balanced, across two languages recruit more EF process in language control. If mTBI impacts EF abilities, particularly inhibitory control, then bilinguals with high proficiency across two languages should make more errors than bilinguals who are less proficient in one language. Additionally, if mTBI disrupts inhibitory control processes in bilingual language control, then eye movement patterns should also differ between groups. Healthy control bilinguals should show shorter gaze durations and proportionally fewer fixations on erred words. Bilinguals with a history of mTBI should make errors despite fixating on the target word and fixating it for longer durations.

Lastly, the second experiment also examined the relationship between the standardized assessment of EF, the *FAVRES*, and EF tasks. While the *FAVRES* has been shown to be reliably sensitive to mTBI, it can be costly, requires specialized training to administer, and takes approximately an hour to complete. If there is a relationship between performance on the FAVRES and other EF tasks, then these tasks could be used to screen individuals for possible EF deficits and determine if there is a need for further testing. This assessment requires participants to identify task relevant information, while simultaneously ignoring task irrelevant information, to arrive at the best possible solution for each scenario. The flanker task measures similar underlying processes as the *FAVRES*, such as the ability to ignore distractors and attend only to the relevant arrow. Thus, there may be a relationship between performance on the flanker task and scores on the *FAVRES*.

Method

Participants. Participants were recruited from Arizona State University undergraduate classes and the Speech and Hearing Clinic of Arizona State University. They received either partial course credit or monetary compensation ($10/hour) for their participation. All participants reported speaking English fluently and reported varying proficiency in Spanish. Language proficiency was measured using a modified version of the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007). Additionally, participants completed a standardized receptive vocabulary measure in English, the *Peabody Picture Vocabulary Test – 3rd Edition, (PPVT-3)*(Dunn & Dunn, 1997) and a standardized receptive vocabulary measure in Spanish, *Receptive One-Word Picture Vocabulary Test in Spanish – 4th Edition (ROWPVT-4 Spanish)*(Martin, 2012) (see Table 6 for language profiles). All participants gave informed consent and the experimental procedures were approved by the Arizona State University Human Subjects Institutional Review Board.

Twenty-two healthy control bilinguals participated in the study. Two participants did not complete both experimental sessions and their data were excluded from analyses.

They reported no history of mTBI, memory, language, or neurological problems. Thirty-five bilingual individuals who reported a history of mTBI participated in the study. Participants who reported a history of mTBI met the Mayo Classification System for Traumatic Brain Injury Severity (e.g., Malec et al., 2007). Ten individuals did not complete both experimental sessions and three individuals did not speak sufficient Spanish to complete all tasks. These individuals' data were not included in the analyses. Healthy control bilinguals and bilinguals with a history of mTBI did not significantly differ in age or education (p_s>.10) (see Table 7 for self-reported medical data).

Stimuli. For the operation span tasks, the same stimuli were used as Experiment 1. The symmetry span task stimuli were taken from Unsworth, et al. (2005). The flanker task stimuli were adapted from Emmorey et al. (2008). Paragraphs for the reading aloud task were taken from Gollan et al. (2014). For the confrontational naming task, 60 of the 126 images from Experiment 1 were used (see Appendix C for images).

Procedure. General experimental procedures were identical to Experiment 1. This experiment consisted of 2 two-hour sessions with tasks presented in random order. Eye-tracking procedures were identical to Experiment 1.

***Standardized Assessments*.** The procedure for the *Peabody Picture Vocabulary Test (3rd Edition) (PPVT-III)* (Dunn & Dunn, 1997), the *Receptive One Word Picture Vocabulary Test – Spanish (4th Edition) (ROWPVT-4 Spanish)* (Martin, 2012), and *Raven's Advanced Progressive Matrices (RAPM)* (Raven, Raven, & Court, 1998) were identical to Experiment 1.

The *Functional Assessment of Verbal Reasoning and Executive Strategies (FAVRES)* (MacDonald, 2005) is designed to be ecologically valid and measures performance on tasks that imitate the complex, functional activities of daily life. Participants were given four problems to read and were asked to provide the best possible solution for each problem by writing their responses in an answer booklet. After solving each problem, the experimenter asked additional questions to determine how the participant arrived at each solution. Responses were scored according to assessment guidelines for overall accuracy, rationale, time to complete each problem, and reasoning. There was no time limit to complete the assessment.

Experimental Tasks. The procedures for forward digit span task, backward digit span task, and operation span tasks were identical to Experiment 1, except that no secondary load task was present. The procedure for the symmetry span task was identical to Experiment 1.

The Corsi blocks task is a visuospatial short term memory task and requires participants to recall the position and order of highlighted blocks or squares. Participants were shown 10 randomly arranged blue squares. Squares changed color, one at a time, from blue to yellow (or were highlighted) for 1000 ms each in a random sequence. Following the sequence, the blue squares appeared again and participants were asked to repeat the sequence by clicking on the squares with the computer mouse. Participants completed four practice trials prior to beginning the experimental portion of the task. Sets contained three to seven highlighted blocks with two trials at each span length and span lengths were presented in progressive order (see Figure 11).

The procedure for the flanker task was similar to Experiment 1. No secondary load task was paired with the arrow decision trials. Each condition (control, go/no-go, and conflict) was presented in two blocks. Control blocks were presented first and last. The go/no-go blocks and conflict blocks alternated between the control blocks and the order was counterbalanced across participants. In total, there were 96 trials in each condition, with 48 trials per block (see Figure 12).

In the switching task, participants were presented with simple geometric figures (i.e., circles or triangles) that were either red or blue in color. Participants were asked to report the color or shape of each figure, as quickly as possible, using the keys marked with a red dot, blue dot, small triangle, or small circle (D, F, H, and J keys respectively). Each trial was preceded by a cue indicating if the participant was to report the color or shape of each figure. The cue for the color task was a color gradient and the cue for the shape task was a row of small black shapes. The cue appeared on the screen 250 ms prior to the geometric figure and remained on the screen during the duration of the trail. The target figure appeared in the center of the screen for 4000 ms or until a response was entered. A practice session consisted of 8 color-judgment trials, 8 shape-judgment trials, and 16 switch trials, in which color and shape judgments were intermixed. Participants received feedback on their performance in the practice session. The experimental session, participants consisted of 12 color-judgment trials, 12 shape-judgment trials, and 24 switch trials presented in three randomized blocks.

The procedure for confrontational naming task, was identical to Experiment 1, but no secondary load task was used. The experimental session contained 60 trials with 20 trials in each language condition (English, Spanish, and Mixed Language).

The procedure for the reading aloud task was similar to Experiment 1, but no secondary load task was used. Participants read paragraphs aloud in four different language conditions: English only, Spanish only, Mixed language with English word order, and Mixed language with Spanish word order, for a total of 16 paragraphs. The order of language conditions was randomized.

Task Scoring. The same scoring procedures were for the operation span tasks, the confrontational naming task, and the reading aloud task as Experiment 1.

Results

Standardized Assessments. For RAPM, there was no difference in performance between bilinguals in the mTBI group and Healthy Controls ($t(40) = 0.88$, p=.386). There was no significant difference in standard scores between groups for the *PPVT-III* (t<1), but there was a marginal difference between groups for the *ROWPVT-4* ($t(41) = 2.25$, p=.030) (see Table 6 for vocabulary scores).

Performance on the *FAVRES* (MacDonald, 2005) was analyzed using a 2(Group: Healthy Control or mTBI) × 4(Assessment Area: Accuracy, Rationale, Time, or Reasoning) mixed ANOVA. For post-hoc analyses, a Bonferroni adjusted alpha of .01 was used for multiple simultaneous comparisons. The main effect of Group was significant ($F(1, 40) = 19.71$, $p<.001$, $\eta_p^2 = .330$). Overall, Healthy Controls outperformed the mTBI group. The main effect of Assessment Area was significant ($F(3, 120) = 28.66$, $p<.001$, $\eta_p^2 = .417$). Standard scores for Time to complete the assessment were higher than standard scores for Accuracy ($t(41) = 6.92$, $p<.001$), Rationale ($t(41) = 5.62$, $p<.001$), and Reasoning ($t(41) = 5.71$, $p<.001$). Additionally, both standard scores for Rationale and Reasoning were higher than standard scores for Accuracy ($t(41) = 3.29$, $p=.002$; $t(41) = 2.75$, $p=.009$, respectively). Interestingly, the Group × Assessment interaction was significant ($F(3, 120) = 6.72$, $p<.001$, $\eta_p^2 = .144$). Healthy controls had higher standard scores than the mTBI group for Accuracy ($t(40) = 4.44$, $p<.001$), Rationale($t(40) = 3.08$, $p=.004$), and Reasoning($t(40) = 3.57$, $p=.001$), but not Time ($t(40) = -.574$, $p=.569$) (see Figure 13).

Experimental Tasks. For each simple span and working memory task, the total items (i.e., digits, words, or squares) recalled and equation accuracy was analyzed using a 2(Group: Healthy Control or mTBI) between subjects ANOVA. For Spanish tasks, the average self-rated proficiency score (across speaking, understanding, and reading) in Spanish was entered as a covariate. Errors were analyzed using a 2(Group: Healthy Control or mTBI) × 6(Error Type: Omissions, Transpositions, Partially Recall, Phonemic Errors, Semantic Errors, or Perseverations) mixed ANOVA for the English operation span task and mixed analysis of covariance (ANCOVA) for the Spanish operation span task (see Table 8). For post-hoc analyses, a Bonferroni adjusted alpha was used for multiple simultaneous comparisons.

Simple Span Tasks. The main effect of Group was not significant for the backward digit span task ($F(1, 40) = 2.60$, $p=.115$), the forward digit span task ($F<1$), or the Corsi Blocks task ($F(1, 40) = 1.05$, $p=.311$). Overall, participants recalled fewer items in the backward digit Span task than either the forward digit span task ($t(41) = 8.40$, $p<.001$) or the Corsi blocks task ($t(41) = 4.28$, $p<.001$) (see Table 8).

Working Memory Tasks. The main effect of Group was not significant for the English operation span task ($F<1$) or the symmetry span task ($F(1, 40) = 3.05$, $p=.088$). For the Spanish operation span task the main effect of Group was not significant ($F(1, 39) = 1.70$, $p=.200$) when average self-rated proficiency in Spanish was entered as a covariate (see Table 8).[12] For equation accuracy, there was no significant main effect of Group for the English operations span task ($F(1, 40) = 2.25$, $p=.141$) or the Spanish operation span task ($F<1$).

For the error analysis in the English operation span task, the main effect of Group was not significant ($F(1, 40) = 2.26$, $p=.141$). The main effect of Error Type was significant ($F(5, 200) = 146.91$, $p<.001$, $\eta_p^2 = .786$).[13] The Group × Error Type interaction was not significant ($F(5, 200) = 1.21$, $p=.308$). For the Spanish operation span task, the main effect of Group was not significant ($F<1$). The main effect of Error Type was significant ($F(5, 195) = 24.44$, $p<.001$, $\eta_p^2 = .385$).[14] The Group × Error Type interaction was not significant ($F(5, 195) = 1.51$, $p=.335$) (see Table 9).

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[12] A 2(Group: Healthy Control or mTBI) × 2 (Task: English operation span or Spanish operation span) mixed ANCOVA was conducted to test for possible Group × Task interaction effects. The overall main effect of Task was significant ($F(1, 39) = 7.985$, $p=.007$, $\eta_p^2 = .170$). All individuals recalled more words in the English version than the Spanish version of the operation span task. Neither the main effect of Group ($F<1$) nor the Group × Task interaction were significant ($F(1, 39) = 2.57$, $p=.117$).

[13] Participants made more Omission Errors than Transmission Errors ($t(42) = 12.02$, $p<.001$), Partial Recall Errors ($t(42) = 13.39$, $p<.001$), Phonemic Errors ($t(42) = 12.63$, $p<.001$), Semantic Errors ($t(42) = 13.75$, $p<.001$), and Perseveration Errors ($t(42) = 13.51$, $p<.001$). Additionally, participants made more Transposition Errors than Partial Recall Errors ($t(42) = 4.50$, $p<.001$) and Semantic Errors ($t(42) = 4.18$, $p<.001$).

[14] Participants made more Omission Errors than Transmission Errors ($t(41) = 13.70$, $p<.001$), Partial Recall Errors ($t(41) = 13.82$, $p<.001$), Phonemic Errors ($t(41) = 14.14$, $p<.001$), Semantic Errors ($t(41) = 15.39$, $p<.001$), and Perseveration Errors ($t(41) = 15.31$, $p<.001$). Participants also made more Transposition Errors than Semantic Errors ($t(41) = 5.88$, $p<.001$) and Perseveration Errors ($t(41) = 3.92$, $p<.001$) and more Phonemic Errors than Partial Recall Errors ($t(41) = 6.31$, $p<.001$), Semantic Errors ($t(41) = 2.86$, $p=.007$) and Perseveration Errors ($t(41) = 3.88$, $p<.001$).

Flanker Task. Correct RTs and accuracy were analyzed using a 2(Group: Healthy Control or mTBI) × 3(Condition: Control, Go/no-go, or Conflict) mixed ANOVA. The conflict effect was calculated by taking the difference in RT and accuracy for incongruent trials compared to congruent trials within the conflict block. The conflict effect was analyzed using a 2(Group: Healthy Control or mTBI) between-subjects ANOVA.

For RTs, the main effect of Group was marginally significant ($F(1, 40) = 3.88$, $p=.056$, $\eta_p^2 = .088$). Healthy Controls were marginally faster than the mTBI group and this difference was driven by differences in RTs in the Go/no-go condition ($t(40) = 2.67$, $p=.011$). The main effect of Condition was also significant ($F(2, 80) = 135.41$, $p<.001$, $\eta_p^2 = .772$). Participants had faster RTs in the Go/no-go condition than either the Control condition ($t(41) = 14.44$, $p<.001$) or the Conflict condition ($t(41) = 12.90$, $p<.001$). Participants also had faster RTs in the Control condition than in the Conflict condition ($t(41) = 3.53$, $p=.001$). The Group × Condition interaction was not significant ($F(2, 80) = 1.48$, $p=.234$) (see Figure 14). For accuracy rates, the main effect of Group, main effect of Condition, and the Group × Condition interaction were not significant (all F's<1).

For the conflict effect on RTs, the main effect of Group was marginally significant ($F(1, 40) = 3.38$, $p=.074$, $\eta_p^2 = .078$). Healthy Controls had a marginally smaller conflict effect that individuals in the mTBI group. For the conflict effect on accuracy, main effect of Group was not significant ($F<1$) (see Table A2).

Switching Task. Correct RTs and accuracy were analyzed using a 2(Group: Healthy Control or mTBI) × 3(Condition: Color, Shape, or Switch) mixed ANOVA. Switching costs reflect the difference between switch (e.g., from shape to color, or vice versa) and repeat trials (repeated color or repeated shape trials) within the Switch condition. Switch costs for RTs and accuracy were analyzed using 2(Group: Healthy Control or mTBI) between-subjects ANOVA.

For RTs, the main effect of Group was not significant (F<1). The main effect of Condition was significant ($F(2, 72) = 21.67$, p<.001, $\eta_p^2 = .376$). Participants had slower RTs in the Switching condition than either the Color ($t(38) = 5.10$, p<.001) or Shape ($t(38) = 5.84$, p<.001) conditions. The Group × Condition interaction was not significant ($F(2, 72) = 1.68$, p=.194). For accuracy, the main effect of Group was not significant ($F(1, 36) = 1.40$, p=.244). The main effect of Condition was significant ($F(2, 72) = 3.79$, p=.027, $\eta_p^2 = .095$). Participants were less accurate in the Switching condition than the Shape condition ($t(38) = 3.63$, p=.001). The Group × Condition interaction was not significant ($F(2, 72) = 1.70$, p=.190). For the Switch cost analysis, the main effect of Group was not significant for either RTs or accuracy (both Fs<1) (see Table 10).

Confrontational Naming Task. Correct RTs, accuracy, and cross language intrusion errors were analyzed using a 2(Group: Healthy Control or mTBI) × 2(Language: English, or Spanish) × 2(Mixing: Single or Mixed) mixed ANCOVA.

The main effect of Group was significant for RTs ($F(1, 36) = 4.91$, p=.033, η_p^2 = .120). Overall, Healthy Controls were faster than the mTBI group. The main effect of Language was significant ($F(1, 36) = 12.47$, p=.001, $\eta_p^2 = .257$). Participants were faster at naming English items than Spanish items. The main effect of Mixing was not significant (F<1). The Group × Language interaction was significant ($F(1, 36) = 7.91$, p=.008, $\eta_p^2 = .180$). For English items, there was no significant difference between Healthy Controls and individuals in the mTBI group; however, there was a significant difference between groups for Spanish items, even after controlling for differences in Spanish proficiency ($F(1, 36) = 11.20$, p=.002, $\eta_p^2 = .232$) (see Figure 15). No other interactions were significant (all Fs<1).

For accuracy, the main effect of Group was marginally significant ($F(1, 39) = 4.06$, p=.051, $\eta_p^2 = .094$). Healthy Controls named marginally more items correctly than the mTBI group, which was driven by differences in Spanish accuracy ($F(1, 39) = 4.39$, p=.043). The main effect of Language was also significant ($F(1, 39) = 50.58$, p<.001, $\eta_p^2 = .565$). Overall, participants named more English items correctly than Spanish items. The main effect of Mixing was not significant ($F(1, 39) = 2.57$, p=.117). The Group × Language interaction was not significant ($F(1, 39) = 2.05$, p=.160). No other interactions were significant (all Fs<1) (see Figure 16). For cross language intrusion errors, no main effect or interaction was significant (all Fs<1).

Reading Aloud Task. Total errors were analyzed using a 2(Group: Healthy Control or mTBI) × 4(Error Type: Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors) mixed ANCOVA (see Table 11 for a summary of errors).[15,16] Gaze duration and proportion of fixations were analyzed 2(Group: Healthy Control or mTBI) × 2(Word Type: Error or Control) mixed ANCOVA.

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[15] The total errors for the target language of an error were analyzed using a 2(Group: Healthy Control or mTBI) × 2(Target Language: English or Spanish) × 4(Error Type: Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors) mixed ANCOVA. The main effect of Group was significant ($F(1, 39) = 5.72$, p=.022, $\eta_p^2 = .128$). The main effect of Language was marginally significant ($F(1, 39) = 3.70$, p=.062, $\eta_p^2 = .087$). The Group × Error Type interaction was marginally significant ($F(3, 117) = 2.69$, p=.050, $\eta_p^2 = .065$) The Language × Error Type interaction was marginally significant ($F(3, 117) = 2.52$, p=.062, $\eta_p^2 = .061$). Participants made more Within Language Errors in Spanish than English ($F(1, 40) = 17.92$, p<.001). No other post-hoc comparisons were significant (all p_s>.10). No other main effects or interactions were significant (all p_s>.10) (see Figure A4).

[16] The total errors were also analyzed using a 2(Group: Healthy Control or mTBI) × 2(Mixing: Single or Mixed) × 4(Error Type: Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors) mixed ANCOVA. The main effect of Group was significant ($F(1, 39) = 5.98$, p=.019, $\eta_p^2 = .133$).

For total errors, the main effect of Group was significant ($F(1, 39) = 5.98$, p=.019, $\eta_p^2 = .133$). Participants in the mTBI group made more errors than Healthy Controls. The main effect of Error Type was not significant ($F(3, 117) = 1.63$, p=.187). The Group × Error Type interaction was significant ($F(3, 117) = 2.84$, p=.041, $\eta_p^2 = .068$). Participants in the mTBI group made significantly more Cross Language Intrusions ($F(1, 39) = 8.31$, p=.006, $\eta_p^2 = .176$) and marginally more Accent errors ($F(1, 39) = 6.67$, p=.014, $\eta_p^2 = .146$) than Healthy Controls, but not Within Language Errors or Omission Errors (p_s>.05) (see Figure 17).

For gaze duration, neither the main effect of Group, nor the main effect of Word Type was significant (both Fs<1). The Group × Word Type interaction was not significant ($F(1, 39) = 2.23$, p=.143) (see Figure 18). For the proportion of fixations, the main effect of Group was significant ($F(1, 39) = 9.14$, p=.004, $\eta_p^2 = .190$). Healthy Controls skipped words more often than bilinguals in the mTBI group. The main effect of Word Type was not significant ($F(1, 39) = 3.01$, p=.091). Interestingly, the Group × Word Type interaction was significant ($F(1, 39) = 8.98$, p=.005, $\eta_p^2 = .187$). For control words, there was no difference in proportion of fixations between groups (F<1), but Healthy Controls skipped error words more than individuals in the mTBI group ($F(1, 39) = 14.35$, p=.005) (see Figure 19).[17]

Neither the main effect of Mixing (F<1), nor the main effect of Error Type ($F(3, 117) = 1.63$, p=.187) were significant. Importantly, the Mixing × Group interaction was significant ($F(1, 39) = 10.89$, p=.002, η_p^2 = .218). Individuals in the mTBI group made significantly more errors than Healthy Control in the Mixed Language condition ($t(40) = 2.83$, p=.007), but not in the Single Language Condition ($t(40) = 4.65$, p=.108). The Group × Error Type interaction was significant ($F(3, 117) = 2.84$, p=.041, $\eta_p^2 = .068$). No other interactions were significant (all p_s>.10) (see Figure A5).

[17] A 2(Group: Healthy Control or mTBI) × 3(Error Type: Cross Language Intrusions, Accent Errors, or Within Language Errors) mixed ANCOVA was also conducted for gaze duration and proportion of fixations. Due to the few number of errors, no main effects or interactions were significant when the analysis also included the different error types as a factor.

Comparisons across Measures. Simple linear regressions were conducted to examine which EF tasks predicted language control errors on the confrontational naming task and the reading aloud task. The following measures were entered as predictors: total words recalled on the operation span tasks, flanker task RTs and accuracy, and switching task RTs and accuracy. These measures were used to predict cross language intrusions on the naming task and Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors on the reading aloud task. Significant and marginally significant predictors are listed in Table 12.

For the naming task, accuracy in the Conflict condition of the flanker task was a significant predictor of cross language intrusions. As accuracy increased, participants made fewer cross language intrusions.

For the reading aloud task, the same EF measures predicted both Cross Language Intrusion and Within Language Errors. As RTs in the Control condition of the flanker task increased, both types of errors increased. Similarly, as RTs in the Go/no-go condition increased, both types of errors increased. Interestingly, accuracy in the Go/no-go condition also predicted Cross Language Intrusion and Within Language Errors. As accuracy increased, both error types decreased. Additionally, RTs on the switching condition of the switching task predicted Cross Language Intrusion and Within Language Errors. As RTs increased, both types of errors increased. Lastly, for Omission Errors, RTs in the Control condition of the flanker task was a marginally significant predictor. As RTs increased, the number of Omissions increased.

Simple linear regressions were also conducted to determine which EF tasks predicted performance on the *FAVRES*. Response times in the Conflict condition and

Go/no-go condition of the flanker task were marginally significant predictors of overall Accuracy on the *FAVRES* (β = -.303, $t(41) = 2.03$, p=.048; β = -.330, $t(41) = 2.24$, p=.031, respectively). As RTs in the Conflict and Go/no-go conditions increased, Accuracy on the *FAVRES* decreased.

Demographic Predictors. Simple linear regressions were conducted to examine which demographic variables and vocabulary measures predicted cross language intrusions on the naming task and Cross Language Intrusions, Accent Errors, Within Language Errors, and Omission Errors on the reading aloud task. Significant and predictors are listed in Table 12. As average proficiency in Spanish increased, all participants made fewer Accent Errors. Likewise, as the ratio of language proficiency in English to Spanish (i.e., Language Balance) increased, the number of Accent Errors decreased.[18]

Additional simple linear regressions were conducted with only the mTBI group to determine which demographic factors could be used to identify a subset of bilinguals that may be at greater risk of language control errors following mTBI. Spanish proficiency and Language Balance were marginally significant predictors of Cross Language intrusions for the mTBI group (β=.520, $t(21) = 2.72$, p=.013; β=.510, $t(21) = 2.65$, p=.015, respectively). As average proficiency in Spanish increased, bilinguals in mTBI group made more Cross Language Intrusions. Likewise, as Language Balance increased, the number of Cross Language Intrusions increased.

[18] Due to a small number of Accent Errors (Range: 0 - 5), regression results should be interpreted with caution.

Discussion

The purpose of the second experiment was to test which EF measures and standardized assessments were sensitive to mTBI in bilinguals. This experiment also examined whether bilinguals with a history of mTBI experience more language control errors than healthy bilingual controls and whether these deficits were related to specific EF abilities. The EF measures were also used to predict performance on a standardized assessment of EF. Lastly, this experiment tested which subset of bilinguals is at greatest risk for language control difficulties following a mTBI. It was expected that bilinguals with mTBI would perform worse than healthy controls on measures of EF, such as the *FAVRES*, flanker task, the switching task, working memory tasks, but not simple span memory tasks. Additionally, it was hypothesized that bilinguals with a history of mTBI would exhibit more language control errors, as measured by a confrontational naming task and reading aloud task. These hypotheses were mostly supported.

The *FAVRES* is designed to be sensitive to mTBI. In this assessment, participants are given four tasks representative of daily functional activities. They are asked to select the best possible solution for each situation and explain why they chose that solution. In the reasoning component of the assessment, participants must explain which facts were relevant, which information was irrelevant, generate additional ideas related to the proposed problem, and predict the consequences of their decision. As expected, bilinguals with a history of mTBI performed worse on three out of four assessment areas compared with healthy bilingual controls. Bilinguals with a history of mTBI had lower accuracy scores, indicating they were less able to select the best possible solution to each problem. They had lower rationale scores which reflects deficits in the ability to explain what information they used to arrive at their decision or solution. Additionally, they had lower reasoning scores than healthy bilingual controls. Although this assessment was normed on a monolingual population, it appears to be a useful clinical tool for identifying mTBI in bilingual participants as well. These findings suggest that complex daily life situations may present persistent problems for individuals with mTBI (e.g., Kashluba, Hanks, Casey, & Millis, 2008; Kendall, Shum, Halson, Bunning, & Teh, 1997; MacDonald & Johnson, 2005).

The relationship between scores on the *FAVRES* and EF tasks was also tested. It was hypothesized that there would be a relationship between performance on the flanker task and performance on the *FAVRES*. This hypothesis was supported. Response times in the conflict and go/no-go conditions of the flanker task predicted overall accuracy on the *FAVRES*. The conflict condition is thought to measure the ability to inhibit interference from distracting stimuli and the go/no-go condition is thought to measure response inhibition (e.g., Costa et al., 2008; Dimoska-Di Marco et al., 2011). It seems that these underlying processes are recruited, or at least related, to more the complex problem solving processes necessary for the *FAVRES*.

The results revealed no group differences on any of the simple span tasks. These results are consistent with previous evidence showing that individuals with mTBI do not show deficits when asked to recall a list of items (e.g., Anderson & Knight, 2010; Ozen et al., 2010). Surprisingly, there were no group differences in either verbal (e.g., operation span tasks) or nonverbal working memory (e.g., symmetry span task) in our sample of participants, contrary to expectations. Prior research has found evidence of deficits in working memory following a mTBI (Dean & Sterr, 2013; Terry et al., 2012). Terry and colleagues found that individuals with acquired mTBI showed worse performance on an operation span task than healthy controls. One possible explanation for the differences between our findings and those of Terry et al. may be related to differences in the sample population. The vast majority of participants in the present study reported a history of only one concussion or mTBI, whereas the participants in the Terry et al. study had a history of multiple mTBIs. Complex working memory tasks, like the ones used in this experiment, may be more sensitive to mTBI in patients with a history of two or more mTBIs or in patients with more moderate TBI.

In the flanker task, healthy control bilinguals showed a marginal advantage in response time compared with bilinguals in the mTBI group, which was driven by faster response times in the go/no-go condition. There were no group differences in either the control condition or the conflict condition. This finding is remarkably consistent with previous evidence (e.g., Dimoska-Di Marco et al., 2011). Dimoska-Di Marco et al. found that individuals with mTBI performed worse on response inhibition tasks (e.g., a go/no-go task) compared with healthy controls, but not on tasks that measured interference inhibition. In this study, interference inhibition was measured using the conflict condition of the flanker task. In the conflict condition, participants saw trials in which the central arrow was flanked by congruent or incongruent arrows. They needed to inhibit the distracting incongruent arrows in favor of the central, target arrow. Bilinguals with mTBI exhibited slower response times than healthy control bilinguals in the condition measuring response inhibition, but no deficits in the condition measuring interference inhibition. It is interesting that across both Experiments 1 and 2, simulated mTBI and TBI slowed response times in the go/no-no condition. One would expect faster response times and more errors in this condition, associated with disinhibition typically observed in TBI patients (e.g., Kim, 2002; Ylvysaker et al., 2005). This finding suggests that mTBI may impair individuals' ability to flexibly switch between the two rules need to perform the go/no-go decision (i.e., 'enter a response' and 'do not enter a response').

For the switching task, it was expected that bilinguals with mTBI would show deficits in performance compared with the healthy control bilinguals. However, no group differences were observed in either response time or accuracy. This finding is inconsistent with previous studies. For example, Caeyenberghs et al. (2014) observed that individuals with mTBI were slower and made more errors during a switching task. A possible explanation for the findings of the present study compared with those of Caeyenberghs et al. may be related to task differences. Caeyenberghs et al. used a trail making task to measure switching ability, while in this experiment, task switching was measured using simple decision to geometric figures. Participants were asked to identify either the shape or color of a simple geometric figure, alternating between these two decisions. This task was chosen because it is frequently used with bilingual populations and has been shown to be sensitive to differences in switching ability between bilinguals and monolinguals (e.g., Garbin et al., 2010; Prior & Gollan, 2011; Prior & MacWhinney, 2009). While this task may reveal cognitive differences between healthy bilinguals and monolinguals, it may not be sufficiently sensitive to detect switching deficits in bilinguals with a history of mTBI.

In the confrontational naming task, bilinguals with mTBI had slower response time and marginally lower accuracy than healthy bilingual controls. However, the groups did not differ on the overall number of cross language intrusion errors. This same pattern was also observed in the first experiment. This finding indicates that mTBI may affect the speed with which bilinguals are able to retrieve words in English and Spanish. However, this task may not be sufficiently sensitive to detect language control deficits following mTBI. This may be because the single word nature of the task is not taxing on language control abilities in bilinguals with mTBI. It is possible that a naming task could be sensitive to language control deficits following a more moderate to severe TBI.

Interesting group differences emerged on the reading aloud task. Bilinguals with mTBI made more errors than healthy controls and this difference was driven by language control errors (cross language intrusions and accent errors). This finding suggests that bilinguals do experience increased language control deficits following a mTBI, particularly in contexts of language switching. Gaze durations did not differ between groups, contrary to hypotheses. Although, bilinguals in the mTBI group made more errors than healthy controls, they did not fixate on either error or control words for longer durations. The proportion of fixations did differ amongst the groups. Healthy control bilinguals were more likely to make errors when they did not fixate a word, or when they skipped a word during reading. This finding is consistent with previous studies and suggests that, for healthy bilinguals, errors may be the result of reduced overt attention (e.g., Gollan et al., 2014). However, in the mTBI group, participants made proportionally similar fixations to both error and control words (89% versus 92%, respectively). This suggests that, following a mTBI, increased language control errors may be partially due to impaired inhibitory control.

This experiment also examined the relationship between language control errors and performance on EF measures. It was expected that bilinguals with greater EF abilities would make fewer language control errors. This hypothesis was partially supported. Performance on the flanker task did predict some of the errors observed in both the confrontational naming task and the reading aloud task.

For the confrontational naming task, accuracy in the conflict condition of the flanker task predicted cross language intrusions. When bilinguals are asked to name an item, both the English and Spanish lexical representations become co-activated (e.g., Dijkstra et al., 1998; Duñabeitia et al., 2010; Libben & Titone, 2009; Marian & Spivey, 2003; Spivey & Marian, 1999). Bilinguals recruit inhibition mechanisms to resolve this conflict and name the item in the target appropriate language (e.g., Green, 1998; Green & Abutalebi, 2013). Performance on the conflict condition of the flanker task may be associated with these same inhibition mechanisms.

For the reading aloud task, performance in the control and go/no-go conditions of the flanker task predicted cross language intrusions and within language errors. This suggests that there may be a relationship between response inhibition and language control processes. This relationship is consistent with models of bilingual language control, such as the IC model and the adaptive control hypothesis. The fact that go/no-go performance predicted both cross language intrusions and within language errors suggests that similar response inhibition processes may underlie both cross language and within language errors in bilinguals. This idea is consistent with connectionist models of bilingual language processing, such as the Bilingual Interactive Activation Model + (Dijkstra & Van Heuven, 2002). This model assumes that a bilinguals' languages are integrated at one level of processing or in one lexicon. During lexical activation, words in both languages become active and irrelevant words must be inhibited through top-down mechanisms. This process is the same for words that are translation pairs across languages (e.g., dog and perro) or words that are semantically related in one language (e.g., dog and cat). The top-down mechanisms recruited to inhibit the contextually inappropriate word may be similar to the response inhibition processes that play a role in go/no-go task performance.

Response times in the switching condition of the switching task also predicted cross language intrusions and within language errors. Previous research has shown that frequent language switching is related to enhanced performance on switching tasks in bilinguals (e.g., Prior & Gollan, 2011; Prior & MacWhinney, 2009) and that bilinguals may recruit similar neural regions for both verbal and nonverbal switching (e.g., Garbin et al., 2010). Thus, the relationship between switching performance and cross language intrusions is not surprising.

It is interesting that the language control errors on the confrontational naming task and reading aloud task were predicted by two different conditions on the flanker task and switching task. This may be due to the different nature of the two language control tasks. In the confrontational naming task, participants must generate the label of an item from its image. In the reading aloud task, participants simply read the printed words. It may be possible that interference inhibition mechanisms are recruited when generating the label of an item, while response inhibition and switching mechanisms are recruited during reading. Current bilingual theories do not make fine grained predictions regarding the exact EF mechanisms responsible for language control under different task demands.

Additional research is required to examine which underlying inhibitory mechanisms are responsible for bilingual language control for different types of linguistic tasks.

Demographic variables predicted accent errors, but not other types of errors for the entire sample of participants. This suggests that language proficiency plays a larger role in accent errors than EF processes. Further, this finding suggests that the underlying processes responsible for accent errors may be different than those responsible for cross language intrusions. However, due to the limited number of accent errors, these relationships should be interpreted with caution.

Demographic variables were also used to predict language control errors in the mTBI group to examine whether a subset of bilinguals may be at greater risk of language control errors following a mTBI. It was hypothesized that bilinguals who were more proficient in two languages, or more balanced across their two languages, would make more language control errors than bilinguals who were dominant in one language. Bilinguals who are more balanced across two languages would experience greater degrees of conflict arising from their two languages and would need to recruit more EF processes to resolve that conflict. It was hypothesized that if mTBI affects the EF processes necessary to control cross-language conflict, then these individuals should experience great language control deficits. The results supported this hypothesis. For bilinguals with a history of mTBI, higher proficiency across both languages resulted in more cross language intrusions compared with bilinguals who were dominant in one language.

General Discussion

The purpose of the present study was to examine the effect of mTBI on bilingual EF and language control using a range of EF and language control measures. In Experiment 1, mTBI was simulated using a secondary load task. In Experiment 2, performance on the EF and language control measures was examined in a group of bilinguals with a history of mTBI and healthy control bilinguals. The findings presented herein provide new insight into the complex relationship between EF and bilingual language control. These findings also have implications for clinicians who assess and treat bilinguals with TBI.

Comparisons across Experiments

The simulated mTBI predicted some, but not all, of the patterns observed in the mTBI participants in Experiment 2. Across both experiments the simple memory span tasks and working memory tasks did not differentiate between no load and load conditions or between bilinguals with mTBI and healthy control bilinguals. It was hypothesized that the simple span tasks would not be sensitive to these conditions. However, it was surprising that the complex working memory tasks were unaffected by load and that bilinguals with mTBI did not perform worse on these task than healthy controls. A possible explanation for these findings could be related to the sample population. All participants were high functioning university students. To succeed in a high level academic environment, they need adequate working memory abilities. Complex working memory tasks may distinguish between bilinguals with mTBI and healthy controls in a sample of individuals recruited from outside the university setting.

Results for flanker task, were similar across Experiments 1 and 2. The secondary load task resulted in slower response times, compared to a no load condition. Similarly, individuals with mTBI were slower, particularly in the go/no-go condition, than healthy controls. Accuracy was unaffected by secondary load or mTBI group status. Although secondary load did not selectively impair performance on the go/no-go condition in Experiment 1, this task may have potential to be used as a clinical screening tool to detect subtle EF deficits following an mTBI.

Similar patterns were also observed across experiments for the confrontational naming task. Relative no load, the use of secondary load task increased response times, and bilinguals with mTBI were slower than healthy bilingual controls. Load did not affect accuracy in the first experiment; however, bilinguals with mTBI were less accurate than healthy bilingual controls. Across both experiments, the number of cross language intrusions was unaffected by load type or mTBI group status. It seems that secondary load, and mTBI, affect the speed with which individual retrieve items in their languages, but not the overall accuracy. It may be that a confrontational naming task is not sufficiently taxing on language control mechanisms to elicit more language control errors in the mTBI group compared to healthy controls. This task may elicit more cross language intrusions in sample of individuals who have an acquired moderate or severe TBI.

For the reading aloud task, secondary load did not increase the number of errors compared with the no load condition. While the pattern of errors was similar across experiments, the group differences observed in Experiment 2 were not predicted using a secondary load task. Bilinguals with mTBI made more errors overall than healthy bilingual controls. This was driven by differences in language control errors, rather than within language errors or omission errors. This finding suggests that mTBI does impact language control abilities in bilinguals. The low level of difficulty of the secondary load task in Experiment 1 may explain the different results across experiments. While participants had to hold a digit or tone in memory to successfully complete the n-back task, they did not have any other distractions while reading the paragraphs. Thus, the secondary load used may not have been sufficiently difficult to increase language control errors in Experiment 1. It may also be the case that the difference in the number of trials is responsible for the discrepant findings. Experiment 1 had a total of 12 paragraphs, while Experiment 2 had a total of 16 paragraphs. Thus, there were more opportunities to err in Experiment 2.

Both experiments revealed similar results for gaze duration. Gaze duration was not affected by secondary load and did not differ across mTBI and healthy control bilinguals. Interestingly, across both experiments, participants had longer gaze durations on error words than control words. This suggests that participant may have some awareness of their errors and may revisit an erred word. Alternatively, this may suggest that participants are less familiar with erred words. It may be possible to distinguish between these two explanations by examining the number of times the eyes left and reentered the word boundaries of an error word. If participants make multiple fixations on an error word, but do not leave the word boundary, this would suggest that they are less familiar with the error word. If their eyes leave and regress back to the erred word, then participants may be aware that they produced the word in error.

The pattern of proportion of fixations was not consistent across experiments. The critical interaction observed in Experiment 2 was not present in Experiment 1. Healthy bilingual controls made fewer fixations on error words than control words. This suggests that inappropriately placed attention may explain some of the errors observed in this group. In contrast, individuals with mTBI made approximately the same number of fixations on error words and control words. Despite fixating on the target word, bilinguals with mTBI still made errors. This may indicate that, in bilinguals with mTBI, errors are partially the result of decreased inhibitory control.

The relationship between EF and language control was inconsistent across experiments. There were no EF measures that significantly predicted language control errors in Experiment 1. This may be related to the reduced number of errors in the first experiment. The secondary load task paired with the language control tasks did not appear to disrupt language control abilities in healthy bilinguals, resulting in few errors. A more difficult or disruptive secondary load task may increase the number of cross language errors and a significant relationship may be observed between performance on the EF tasks and errors. Interestingly, performance on the flanker task and switching task was related to language control errors in Experiment 2. Better overall performance on these EF measures was predictive of fewer errors. This suggests that there are underlying inhibition and switching processes related to language control and, if these are impacted by mTBI, then language control deficits increase. This finding is consistent with prior evidence showing a relationship between EF and language control (e.g., Gollan et al., 2011) and with the assumptions of the IC model and adaptive control hypothesis (e.g., Green, 1998; Green & Abutalebi, 2013).

Clinical Implications

The findings of the currently study have important clinical implications. Bilinguals with mTBI may have language control deficits in addition to the common EF deficits observed in patients with mTBI. Clinicians working with bilinguals with a history of TBI may need to assess these possible language control deficits. They may need to assess if patients are experiencing increased difficulty retrieving words in one language compared to the other. Depending on the communication needs of the patients, clinicians may also need to determine if bilinguals with acquired TBI are experiencing difficulty switching between languages or translating from one language into the other. These difficulties could affect daily communication for bilingual individuals. For example, difficulty translation or switching between languages can affect young adult bilinguals if they serve as the primary translator in the family or if they work in a field where frequent language switching is necessary. Additionally, if patients report language control problems, further in depth executive function testing may be warranted. Language processing deficits may be symptomatic of deeper executive dysfunction which manifests as language control deficits.

This study may also provide clinicians with some possible tasks to use as screening tools for EF and language control deficits. For example, performance in the conflict and go/no-go condition were predictive of overall accuracy on the *FAVRES* in Experiment 2. Future research may investigate how the flanker task could be used clinically as an effective tool to detect mild EF deficits in this clinical population. Additionally, the language control measures used in the present study might be used as possible screening tools to measure language control deficits following TBI in bilinguals.

More research is necessary to determine exactly how to use these tasks, but the results of the present study are promising.

Limitations and Future Directions

One limitation of the present study is that the secondary load task used in Experiment 1 may not have been sufficiently difficult to disrupt language control processes. As a result, secondary load did not increased the overall number of language control errors. Due to the few number of errors, it was not possible to detect a significant relationship between performance on EF tasks and language control errors. In a follow-up experiment, the secondary load task has been manipulated to be more cognitively demanding. It is expected that this increase in difficulty will result in more language control errors and significant relationships between EF and these errors, similar to Experiment 2.

Another limitation of the present study is that only 25% of the bilinguals with mTBI provided medical documentation regarding their diagnosis. The remaining participants did not retain copies of their medical documents or never sought medical attention. The history of a mTBI is based on self-report. However, this study was advertised for both healthy bilingual controls and bilinguals with a history of mTBI. Regardless of mTBI status, Spanish-English bilinguals were able to participate in the study and were assigned to a group based on self-report. There was no additional incentive for individuals who reported a history of mTBI.

Future studies should examine executive function deficits related to language control in bilinguals in the larger community and those with moderate to severe brain injuries. It may be possible that the patterns observed in the present study will be more pronounced in bilinguals with more severe forms of TBI, or different from the patterns observed with a mTBI sample. This will shed light on the impact of mTBI on EF and language control across of spectrum of TBI severity. Future studies can also examine how the tasks used in the current study may be utilized in the clinical setting to identify EF and language control deficits in bilinguals with mTBI.

This is the first study to directly investigate the impact of mTBI on EF and language control in bilingual individuals. The findings of this study provide insight into the complex relationship between EF and language control in bilinguals and how this relationship is affected by mTBI. Ultimately, these findings will provide a benefit to the clinicians who assess and treat bilinguals, and the patients who receive those services.

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Table 1

Language Profile for Participants in Experiment 1.

Spanish Proficiency		English Proficiency	
Daily Use	25.03% (14.69)	Daily Use	74.97% (14.69)
Daily Reading	14.10% (14.04)	Daily Reading	85.90% (14.04)
Age of Acquisition	2.95 (6.28)	Age of Acquisition	3.59 (3.18)
Age Fluent	6.11 (5.91)	Age Fluent	6.37 (3.40)
Age Began Reading	9.23 (4.97)	Age Began Reading	5.92 (1.97)
Age Fluent Reading	11.33 (5.33)	Age Fluent Reading	8.00 (2.45)
Proficiency		Proficiency	
Speaking	7.85 (2.23)	Speaking	9.26 (0.97)
Understanding	8.71 (1.54)	Understanding	9.67 (0.62)
Reading	7.96 (1.75)	Reading	9.64 (0.67)
Vocabulary	77.37 (13.42)	Vocabulary	95.74 (7.64)

Note: Self-ratings for proficiency questions are based on a 10-point scale. Standard deviations are in parentheses. Vocabulary refers to performance on Peabody Picture Vocabulary Test – 3rd Edition (English) and Receptive One-Word Picture Vocabulary Test – 4th Edition (Spanish).

Table 2

Mean Items Recalled on Complex and Simple Span Tasks by Load Type

	No Load	Verbal Load	Nonverbal Load
Forward Digit Span Task	40.69 (6.74)	44.67 (3.34)	43.46 (4.59)
Backward Digit Span Task	37.64 (7.92)	36.15 (7.09)	38.17 (7.76)
English Operation Span Task	26.00 (8.49)	25.17 (9.83)	34.83 (9.68)
Spanish Operation Span Task	24.92 (9.41)	22.00 (10.60)	21.77 (9.83)

Note: Standard deviations are in parentheses.

Table 3

Raw Errors on Operation Span Tasks by Load Type

	No Load	Verbal Load	Nonverbal Load
English Operation Span Task			
Omission Errors	15.57 (8.43)	17.75 (11.18)	10.25 (5.74)
Transposition Errors	2.21 (2.29)	2.00 (1.76)	1.50 (1.78)
Partial Recall Errors	1.00 (1.18)	0.33 (0.89)	0.17 (0.39)
Phonemic Errors	0.86 (0.77)	0.58 (0.99)	0.58 (0.67)
Semantic Errors	0.36 (0.50)	0.08 (0.29)	0.08 (0.29)
Perseveration Errors	1.00 (0.96)	0.67 (1.23)	0.25 (0.62)
Spanish Operation Span Task			
Omission Errors	17.17 (8.49)	19.86 (8.93)	20.46 (7.67)
Transposition Errors	3.17 (2.12)	3.79 (2.86)	3.31 (2.66)
Partial Recall Errors	0.58 (0.67)	0.57 (0.85)	0.85 (0.99)
Phonemic Errors	1.42 (1.88)	1.50 (1.29)	0.69 (1.11)
Semantic Errors	0.25 (0.45)	0.21 (0.43)	0.53 (0.66)
Perseveration Errors	0.33 (0.49)	0.57 (0.94)	0.54 (0.88)

Note: Standard deviations are in parentheses.

Table 4

Total Number of Errors Produced in Reading Aloud Task by Language and Load Type

	Language Condition			
	Single Language		Mixed Language	
	English Only	Spanish Only	English Word Order	Spanish Word Order
No Load				
English[a]				
Cross Language Intrusion	0	-	35	31
Accent Error	0	-	2	7
Within Language Error	14	-	13	7
Omission Error	25	-	7	13
Spanish[a]				
Cross Language Intrusion	-	0	14	14
Accent Error	-	2	0	2
Within Language Error	-	31	11	15
Omission Error	-	14	0	9
Verbal Load				
English[a]				
Cross Language Intrusion	0	-	24	34
Accent Error	0	-	11	11
Within Language Error	29	-	15	10
Omission Error	22	-	8	6
Spanish[a]				
Cross Language Intrusion	-	0	18	11
Accent Error	-	2	3	5
Within Language Error	-	40	10	19
Omission Error	-	19	1	6
Nonverbal Load				
English[a]				
Cross Language Intrusion	0	-	19	28
Accent Error	0	-	7	8
Within Language Error	25	-	17	9
Omission Error	18	-	3	8
Spanish[a]				
Cross Language Intrusion	-	1	13	22
Accent Error	-	0	6	4
Within Language Error	-	28	19	15
Omission Error	-	27	1	6

[a] Language refers to target language. Paragraphs written in English presented no opportunities to err on Spanish target words, and paragraphs written in Spanish presented no opportunities to err on English target words.

Table 5

Mean Accuracy for Load Type across all Tasks

	Load Type	
	Verbal Load Accuracy	Nonverbal Load Accuracy
Flanker	93%	87%
Reading Aloud Task	85%	76%
Naming	93%	86%
Forward Digit	88%	86%
Backward Digit	92%	88%
Operation Span English	95%	92%
Operation Span Spanish	87%	80%

Table 6

Language Profiles for Participants in Experiment 2.

	Spanish Proficiency		English Proficiency
Healthy Control (*N*=20)			
Daily Use	26.25% (16.83)	Daily Use	73.75% (16.83)
Daily Reading	23.10% (20.49)	Daily Reading	76.90% (20.49)
Age of Acquisition	1.50 (5.84)*	Age of Acquisition	5.15 (6.45)
Age Fluent	4.90 (5.78)*	Age Fluent	7.55 (6.54)
Age Began Reading	7.63 (5.72)*	Age Began Reading	7.05 (5.81)
Age Fluent Reading	9.26 (5.68)*	Age Fluent Reading	8.80 (5.89)
Proficiency		Proficiency	
Speaking	8.05 (1.54)*	Speaking	9.35 (0.81)
Understanding	9.60 (0.75)*	Understanding	9.80 (0.52)
Reading	7.80 (2.28)	Reading	9.60 (0.82)
Vocabulary	78.75 (13.69)	Vocabulary	99.10 (10.40)
mTBI (*N*=22)			
Daily Use	16.23% (14.86)	Daily Use	83.77% (14.86)
Daily Reading	10.05% (18.36)	Daily Reading	90.41% (18.49)
Age of Acquisition	8.59 (6.83)	Age of Acquisition	1.68 (3.51)
Age Fluent	11.64 (6.65)	Age Fluent	5.32 (5.30)
Age Began Reading	12.02 (3.79)	Age Began Reading	4.66 (2.26)
Age Fluent Reading	14.47 (3.69)	Age Fluent Reading	7.77 (4.80)
Proficiency		Proficiency	
Speaking	5.68 (2.17)	Speaking	9.41 (1.14)
Understanding	6.30 (2.39)	Understanding	9.68 (0.89)
Reading	6.30 (2.26)	Reading	9.50 (1.18)
Vocabulary	69.63 (12.59)	Vocabulary	100.50 (9.61)

Note: Self-ratings for proficiency questions are based on a 10-point scale. Standard deviations are in parentheses. Vocabulary refers to standard score on Peabody Picture Vocabulary Test – 3rd Edition (English) and Receptive One-Word Picture Vocabulary Test – 4th Edition (Spanish). An independent samples t-test was conducted to compare language profile differences in the Healthy Control and mTBI groups. A Bonferroni corrected alpha of .005 was used for multiple simultaneous comparisons.
$*p \leq .005$

Table 7

Self-reported Medical Data for Participants with mTBI.

	Participants with mTBI
Time since injury (months) (*N*=22)	21.3 (3 – 74)
Loss of consciousness (minutes) (*N*=8)	3.5 (0.2 – 5)
Symptoms experienced at time of mTBI (*N*=22)	
Double vision	41%
Loss of memory	45%
Dizziness	82%
Loss of balance	77%
Headache	86%
Blurred vision	59%
Disorientation	80%
Residual Symptoms (*N*=19)	
Difficulty with sustained attention	84%
Difficulty shifting attention	47%
Easily fatigued	58%
Easily distracted	68%
Difficulty recalling recently learned information	68%
Difficulty retrieving long-term memories	53%
Difficulty formulating new ideas/reasoning	47%
Personality changes	36%

Note. Range is in parentheses.

Table 8

Mean Items Recalled on Simple Span and Complex Span Tasks by Group

	Healthy Control (*N*=20)	mTBI (*N*=22)
Backward digit span	36.40 (6.56)	39.41 (5.52)
Forward digit span	43.30 (3.66)	44.63 (4.88)
Corsi blocks	41.55 (4.78)	43.05 (4.66)
Operation span – English	28.15 (8.88)	30.13 (7.60)
Operation span – Spanish	28.65 (7.69)	23.05 (7.59)
Symmetry span	21.20 (7.72)	24.73 (5.23)

Note: Standard deviations are in parentheses. The adjusted means for the Spanish operation span task were (M = 27.67) and (M = 23.94) for the Healthy Control and mTBI groups, respectively.

Table 9

Raw Errors on Operation Span Tasks by Group

	Healthy Control (*N*=20)	mTBI (*N*=22)
English Operation Span Task		
Omission Errors	14.55 (6.80)	12.27 (5.95)
Transposition Errors	2.15 (1.76)	1.45 (1.30)
Partial Recall Errors	0.50 (0.76)	0.59 (0.91)
Phonemic Errors	0.97 (0.22)	1.18 (0.25)
Semantic Errors	0.65 (1.14)	0.32 (0.89)
Perseveration Errors		
Spanish Operation Span Task		
Omission Errors	15.15 (5.50)	20.36 (8.31)
Transposition Errors	2.50 (1.64)	1.18 (1.30)
Partial Recall Errors	1.20 (1.40)	1.23 (1.31)
Phonemic Errors	1.60 (1.14)	2.86 (2.34)
Semantic Errors	0.25 (0.44)	0.41 (0.67)
Perseveration Errors	0.85 (1.18)	0.86 (1.08)

Note: Standard deviations are in parentheses.

Table 10

Correct Response Times, Accuracy, and Switch Costs on Switching Task by Group

	Healthy Control (*N*=20)	mTBI (*N*=22)
Response Time		
Color	740.46 (44.31)	811.49 (46.71)
Shape	770.21 (32.31)	744.93 (34.06)
Switch	898.72 (47.72)	940.33 (50.30)
Switch Costs	167.18 (30.73)	185.75 (32.40)
Accuracy		
Color	97.95% (4.57%)	93.56% (11.34%)
Shape	97.75% (5.29%)	98.22% (3.42%)
Switch	94.80% (5.37%)	93.78% (6.02%)
Switch Costs	-5.00% (8.26%)	-4.11% (7.58%)

Note: Standard deviations are in parentheses.

Table 11

Total Number of Errors Produced of Each Type by Language Condition and Group

	Language Condition			
	Single Language		Mixed Language	
	English Only	Spanish Only	English Word Order	Spanish Word Order
Healthy Control				
English[a]				
Cross Language Intrusion	0	-	33	32
Accent Error	0	-	6	9
Within Language Error	7	-	11	7
Omission Error	15	-	11	5
Spanish[a]				
Cross Language Intrusion	-	2	15	10
Accent Error	-	0	1	3
Within Language Error	-	59	15	16
Omission Error	-	21	4	10
mTBI				
English[a]				
Cross Language Intrusion	0	-	47	58
Accent Error	0	-	10	21
Within Language Error	29	-	18	7
Omission Error	8	-	15	5
Spanish[a]				
Cross Language Intrusion	-	5	31	15
Accent Error	-	9	11	9
Within Language Error	-	87	39	58
Omission Error	-	32	7	9

[a] Language refers to target language. Paragraphs written in English presented no opportunities to err on Spanish target words, and paragraphs written in Spanish presented no opportunities to err on English target words.

Table 12

Executive Function Measures and Demographic Variables that Predict Language Errors on the Naming and Reading Aloud Tasks for all Participants

	Naming Task	Reading Aloud Task			
	Cross Language Intrusions	Cross Language Intrusions	Accent Errors	Within Language Errors	Omission Errors
Executive Function Predictors					
Flanker Control Condition Response Time		*β*=.350 *t*(41) = 2.37 *p*=.023		*β*=.455 *t*(41) = 3.23 *p*=.002	*β*=.312, *t*(41) = 3.23 *p*=.044
Flanker Go/no-go Condition Accuracy		*β*= -.324 *t*(41) = 2.17 *p*=.036		*β*= -.502 *t*(41) = 3.67 *p*=.001	
Flanker Go/no-go Condition Response Time		*β*=.321 *t*(41) = 2.14 *p*=.038		*β*=.562 *t*(41) = 430 *p*<.001	
Flanker Conflict Condition Accuracy	*β*= -.479 *t*(41) = 3.45 *p*=.001				
Switching Task Switching Condition Response Time		*β*=.544 *t*(41) = 3.89 *p*<.001		*β*=.579 *t*(41) = 4.26 *p*<.001	
Demographic Predictors					
Average Spanish Proficiency			*β*= -.490 *t*(41) = 3.56 *p*=.001		
Language Balance			*β*= -.549 *t*(41) = 4.15 *p*<.001		

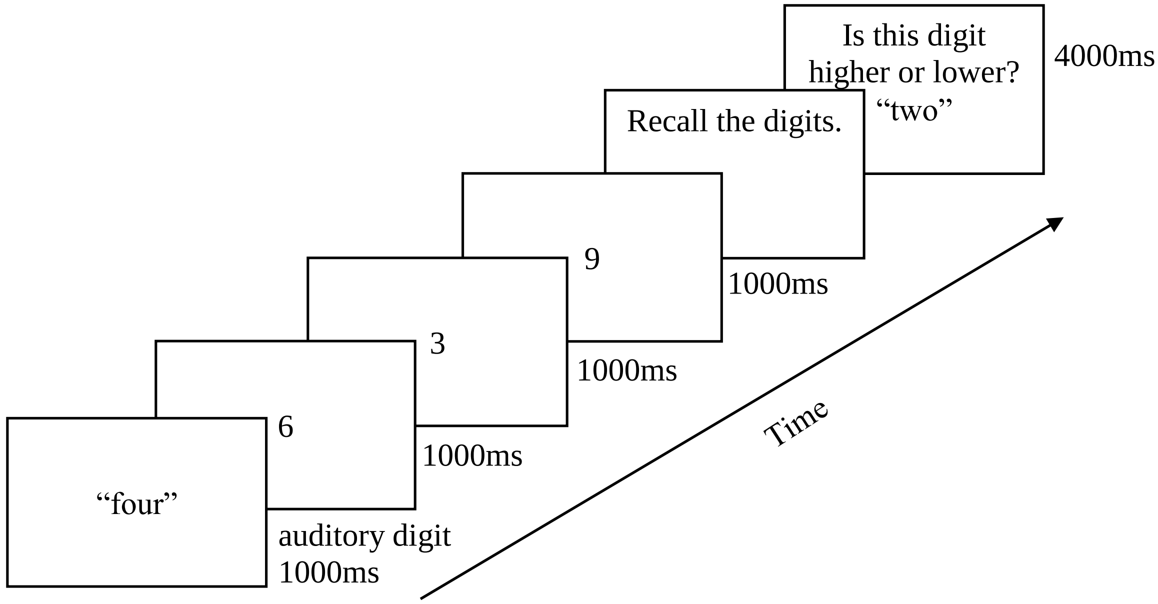

Figure 1. Procedure for forward digit span task for a set length of three paired with digit or verbal load.

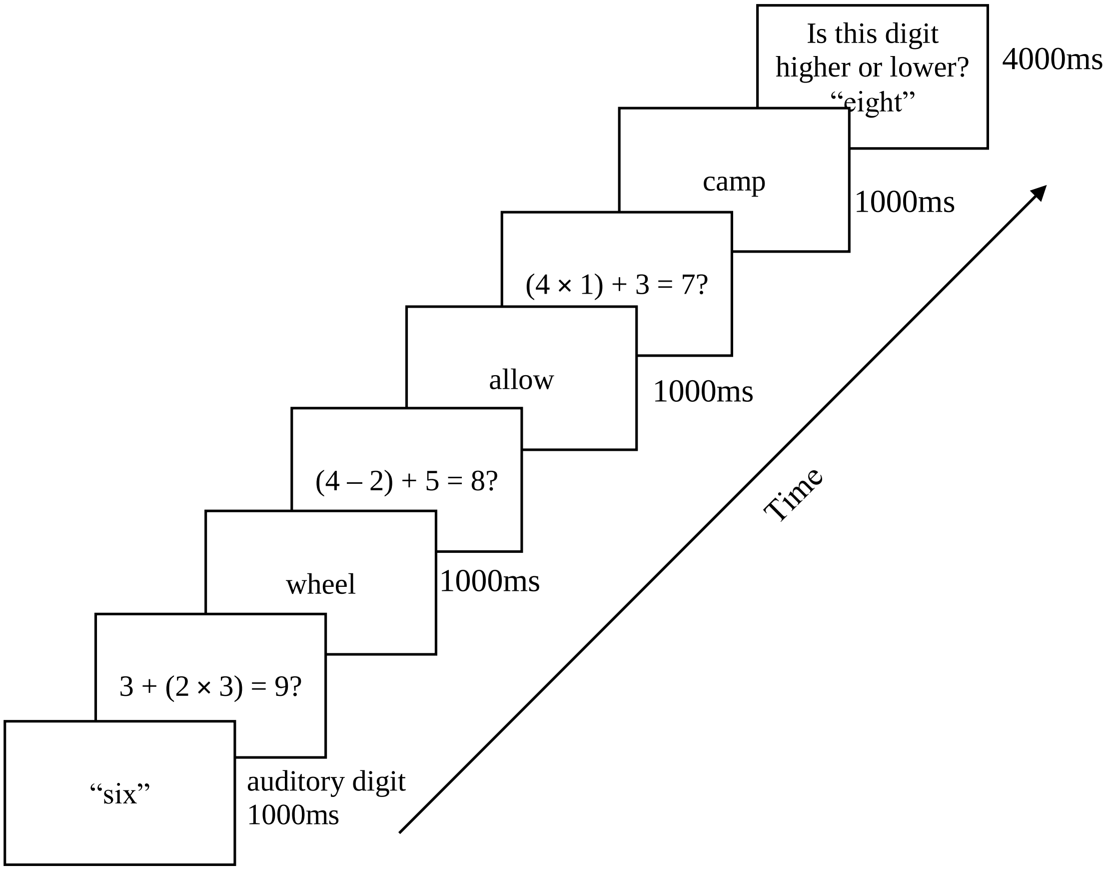

Figure 2. Procedure for operation span task for a set length of three paired with digit or verbal load.

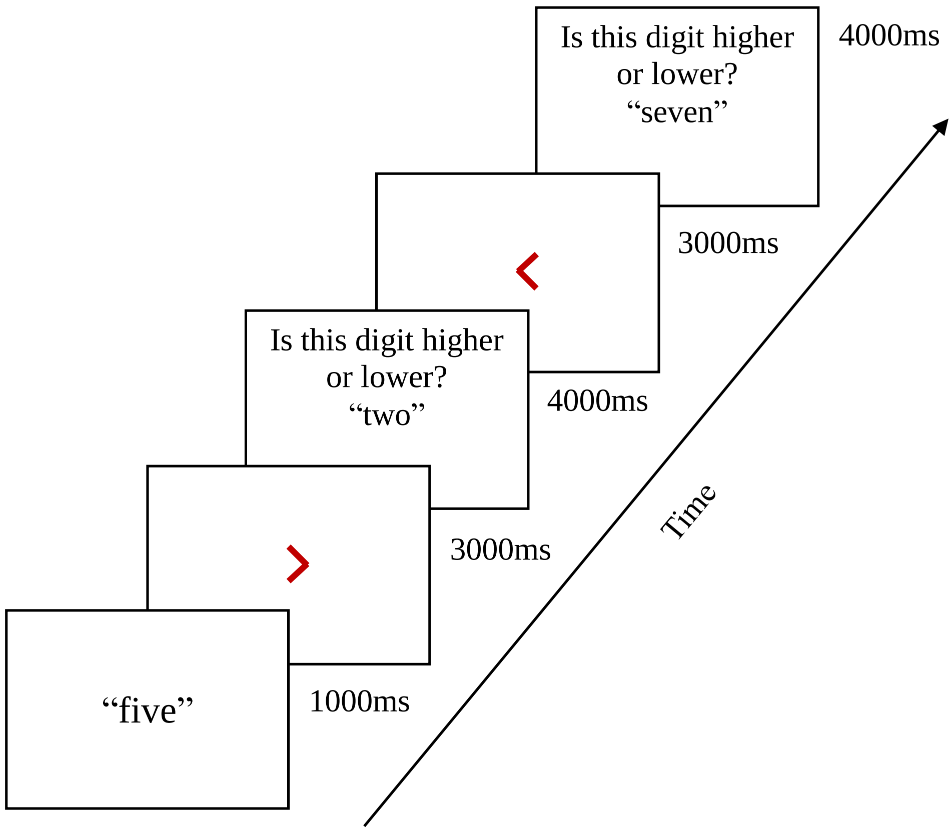

Figure 3. Procedure for flanker task for control condition paired with digit or verbal load.

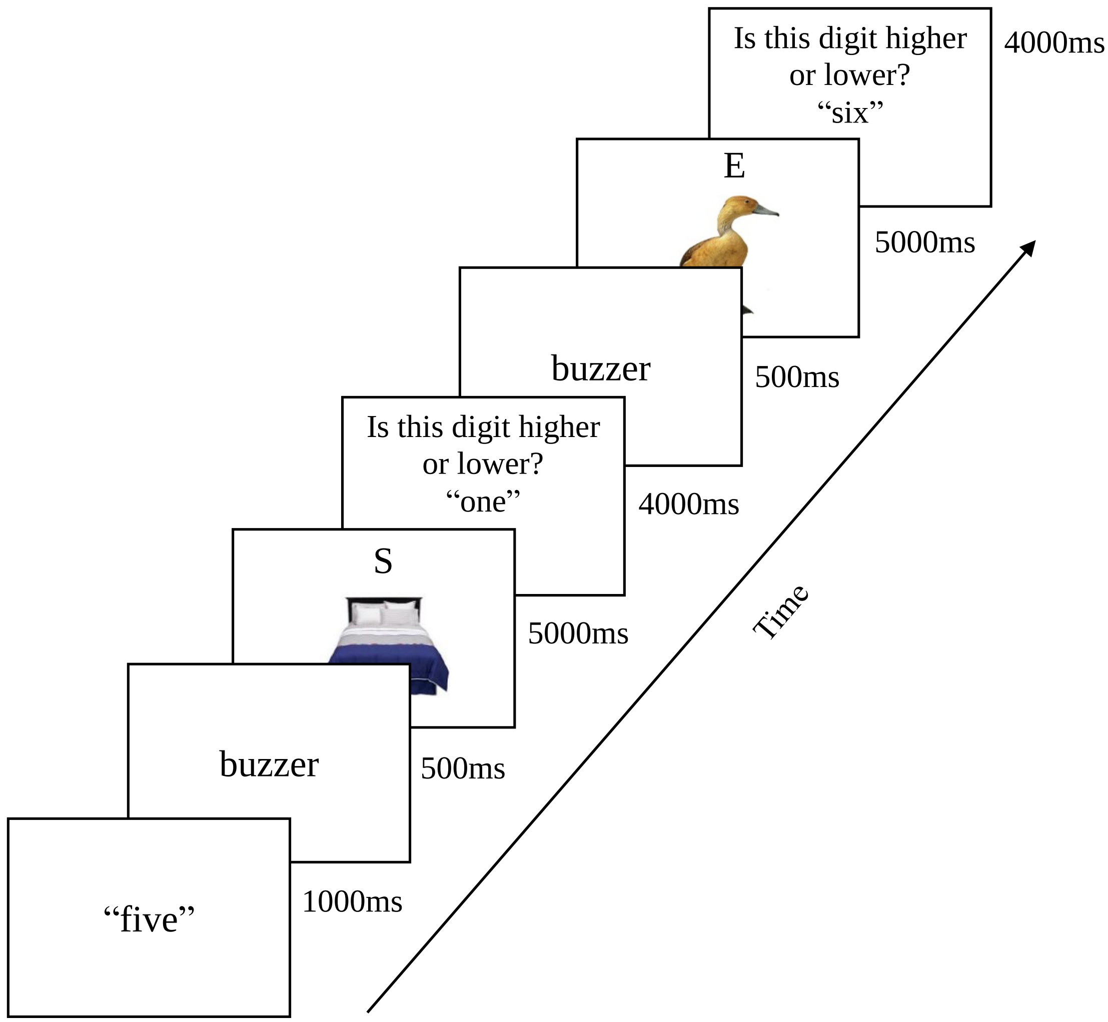

Figure 4. Procedure for confrontational naming task for Mixed Language Condition paired with digit or verbal load.

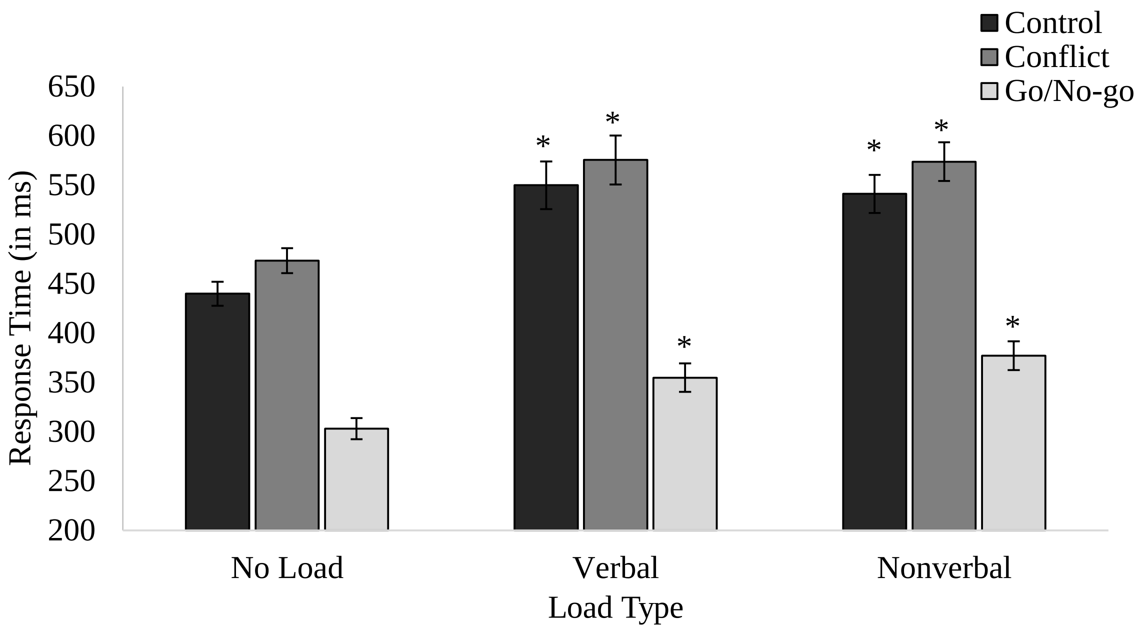

Figure 5. Mean correct response times for flanker task by Load Type and Condition. Error bars represent standard error of the mean. * Denotes significantly different from No Load condition (p<.008).

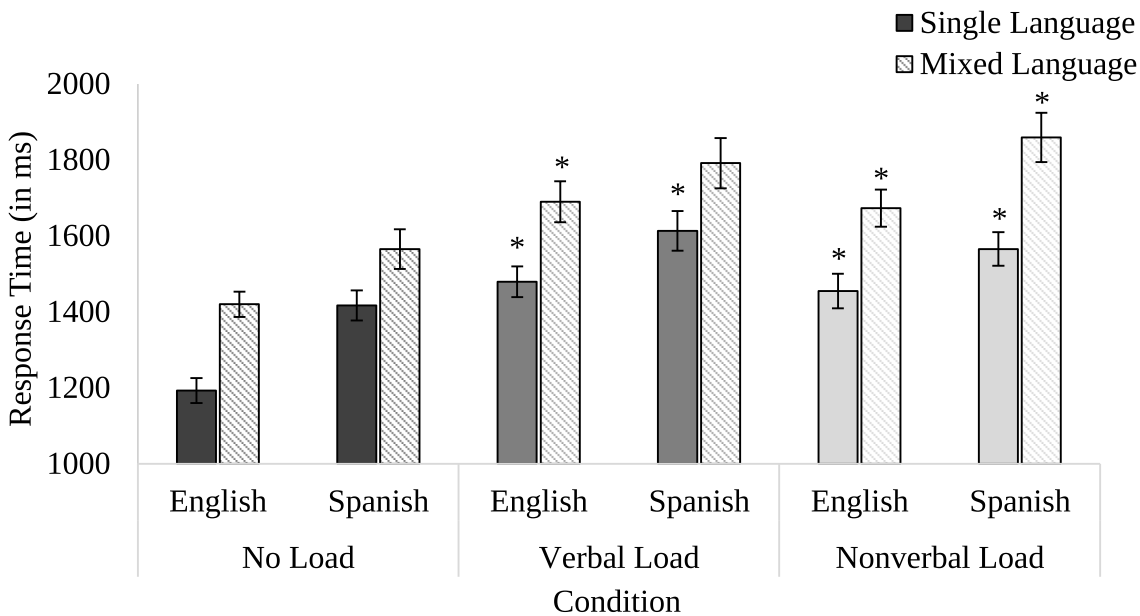

Figure 6. Mean correct response times for confrontational naming task by Load Type, Language, and Mixing Condition. Error bars represent standard error of the mean.
* Denotes significantly different from No Load condition (p<.006).

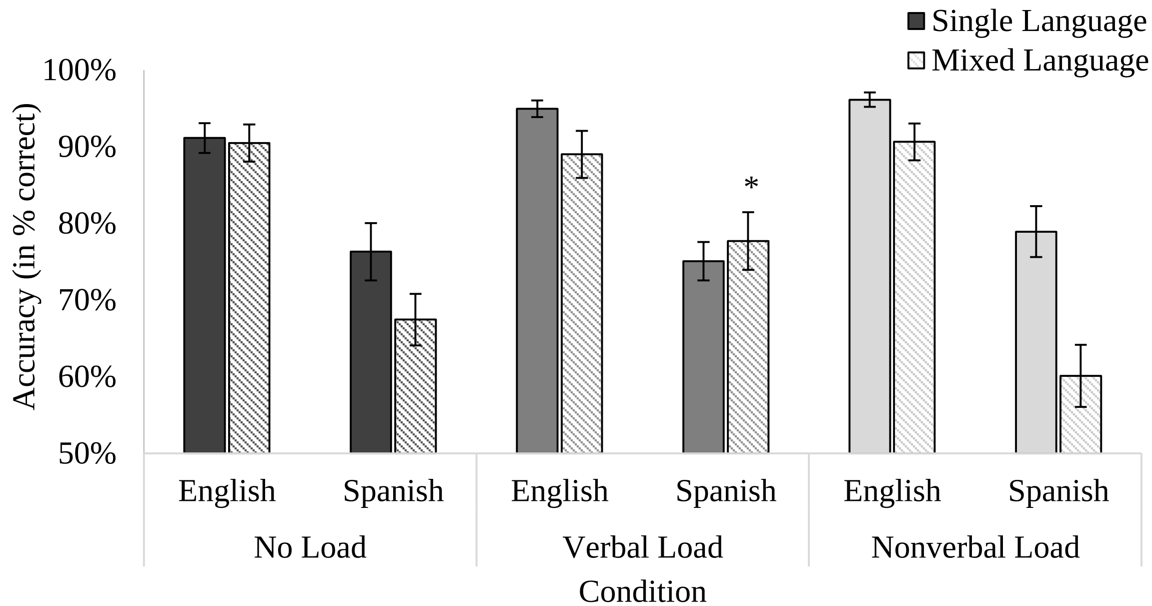

Figure 7. Mean accuracy for confrontational naming task by Load Type, Language, and Mixing Condition. Error bars represent standard error of the mean. * Denotes significantly different from No Load condition (p<.006).

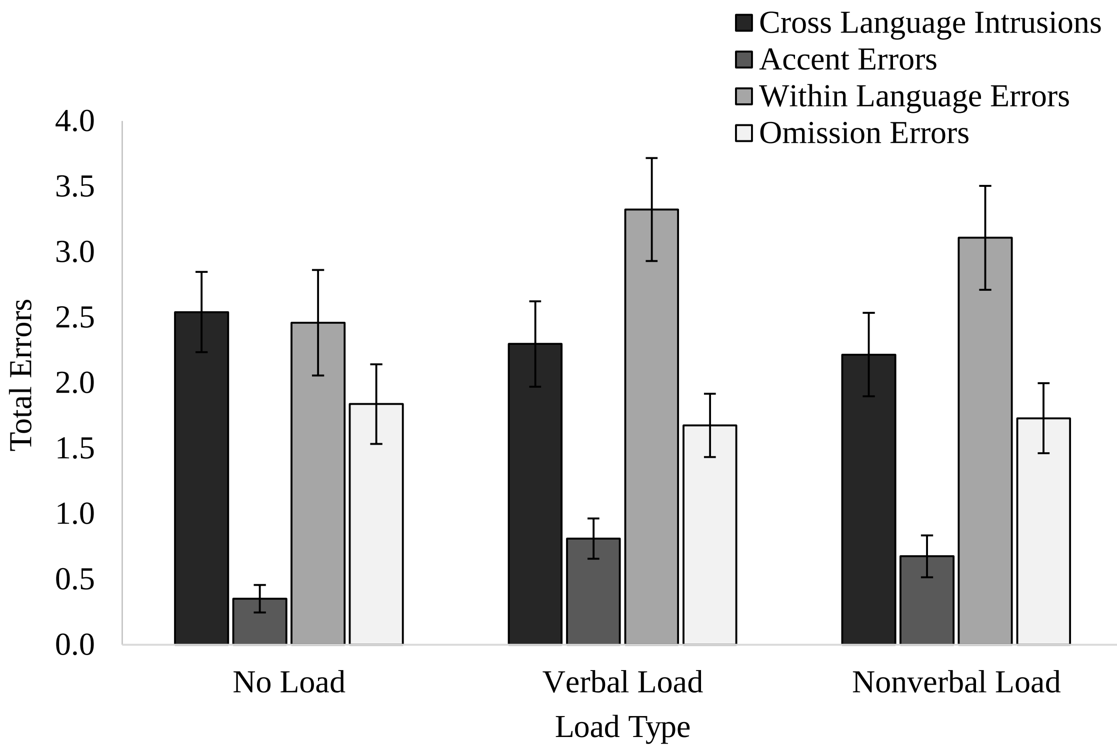

Figure 8. Total errors for the reading aloud task by Load Type. Error bars represent standard error of the mean.

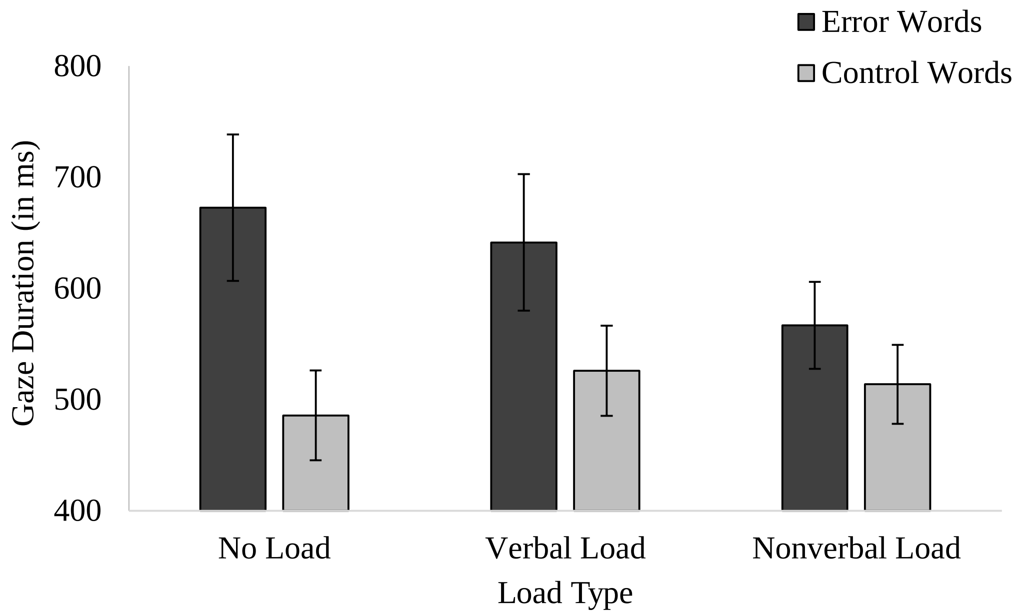

Figure 9. Gaze duration for the reading aloud task by Load Type. Error bars represent standard error of the mean.

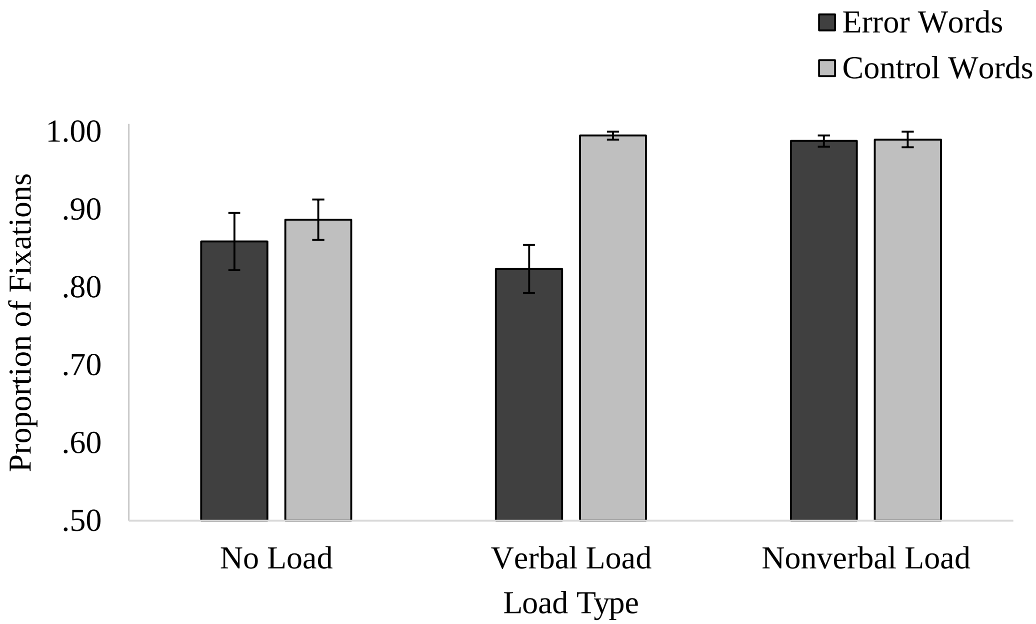

Figure 10. Proportion of fixations for the reading aloud task by Load Type. Error bars represent standard error of the mean.

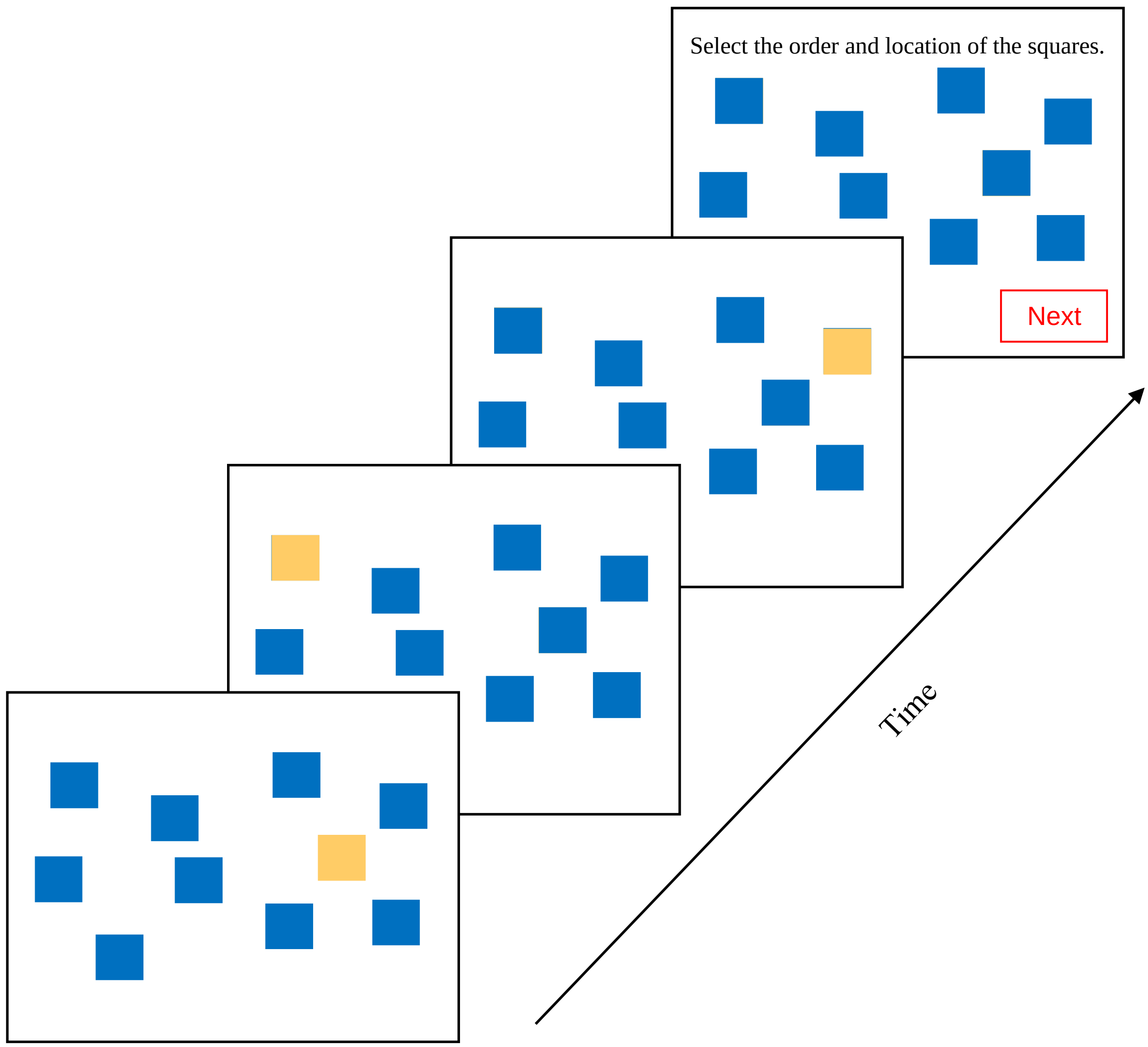

Figure 11. Procedure for Corsi blocks task for a set length of three.

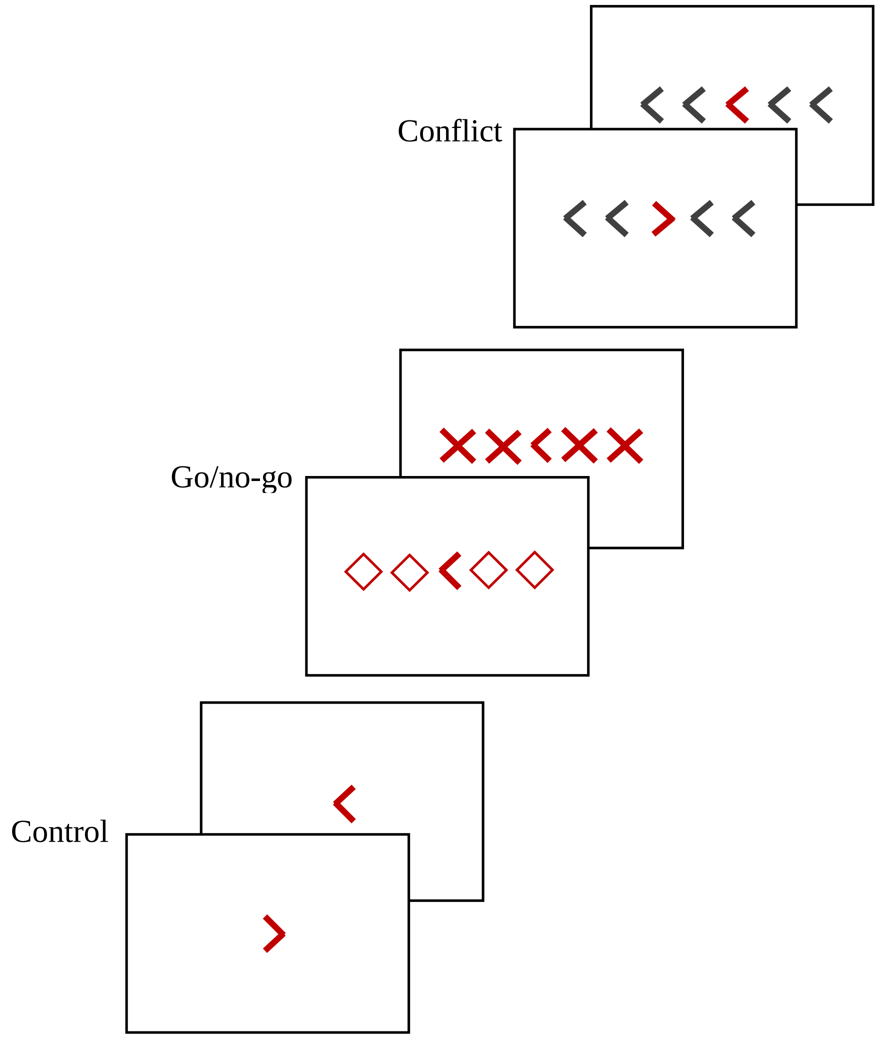

Figure 12. Sample trials for flanker task for each condition.

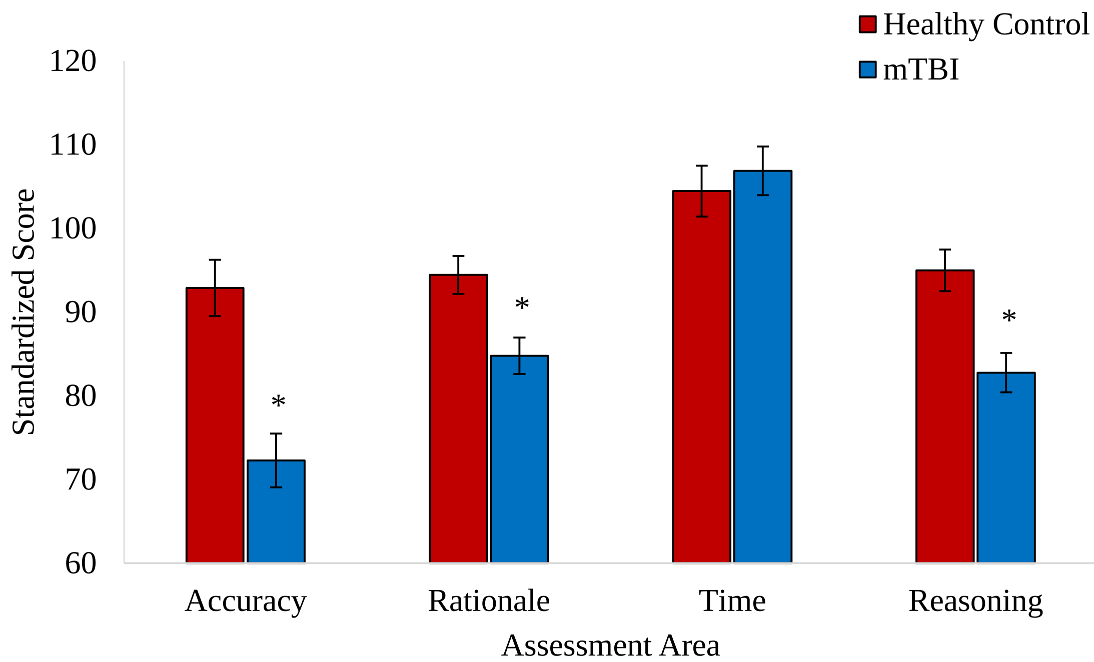

Figure 13. Performance on the Functional Assessment of Verbal Reasoning and Executive Strategies Assessment by Assessment Area and Group. *Denotes significantly different from Healthy Controls (*p*<.013).

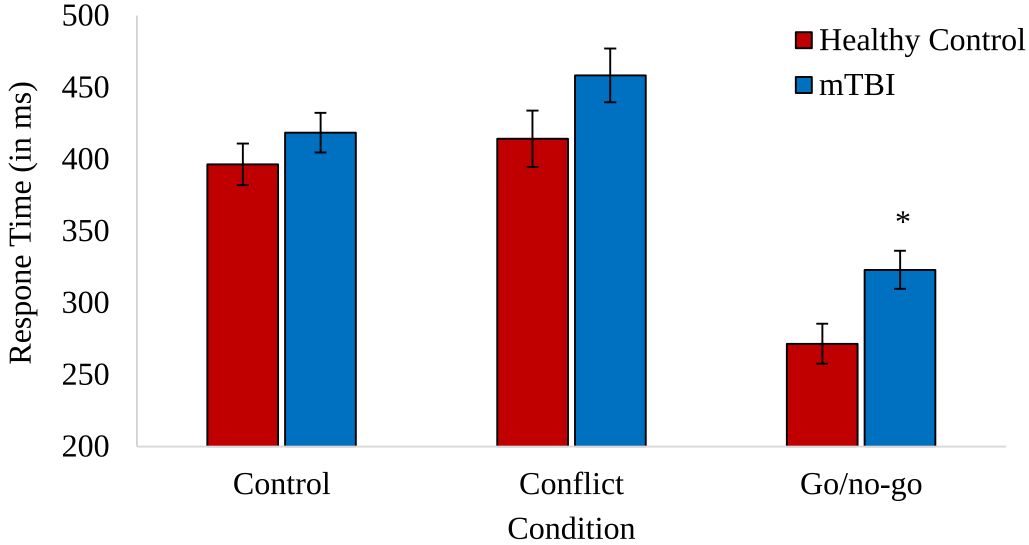

Figure 14. Mean correct response times on the flanker task by Condition and Group. *Denotes significantly different from Healthy Controls (p<.017).

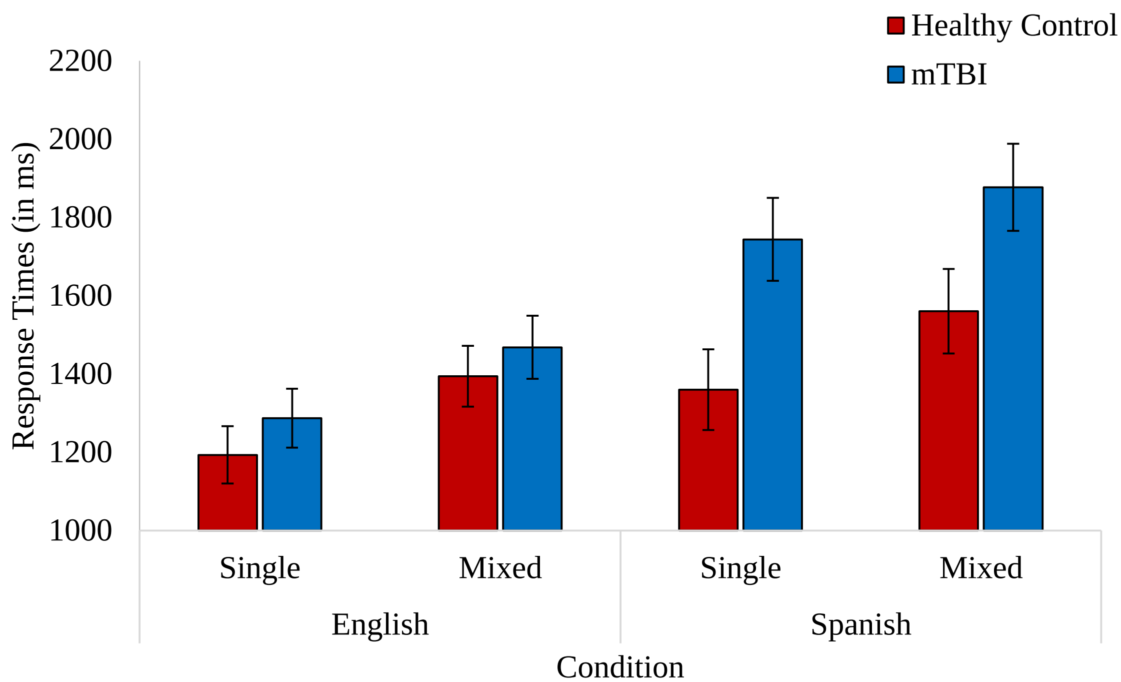

Figure 15. Mean correct response times on the confrontational naming task by Condition and Group. *Denotes significantly different from Healthy Controls (p<.013).

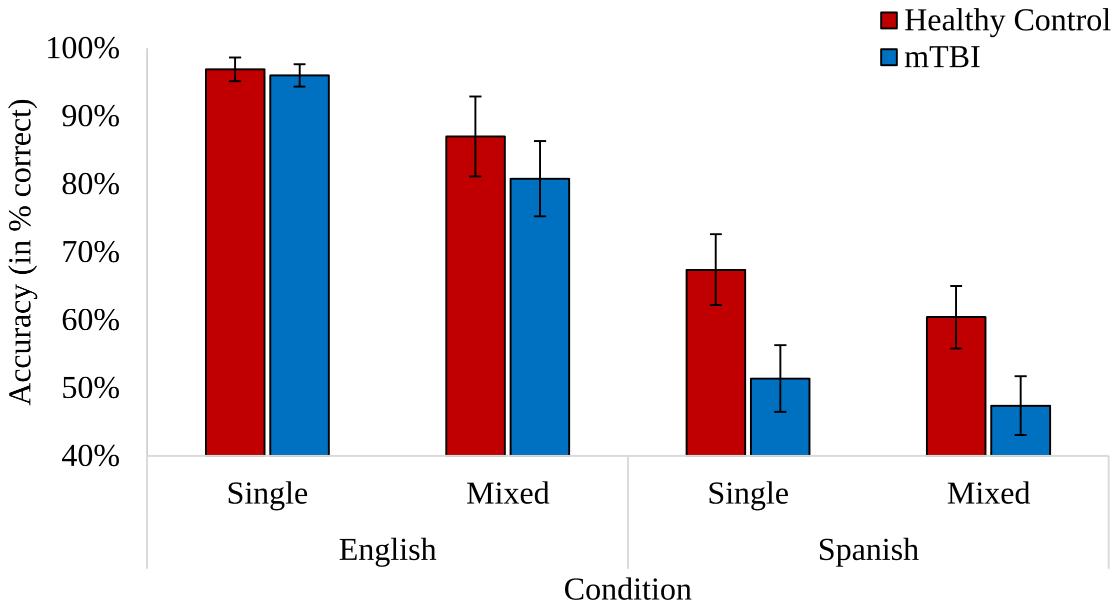

Figure 16. Accuracy on the naming task by Condition and Group. *Denotes significantly different from Healthy Controls (*p*<.013).

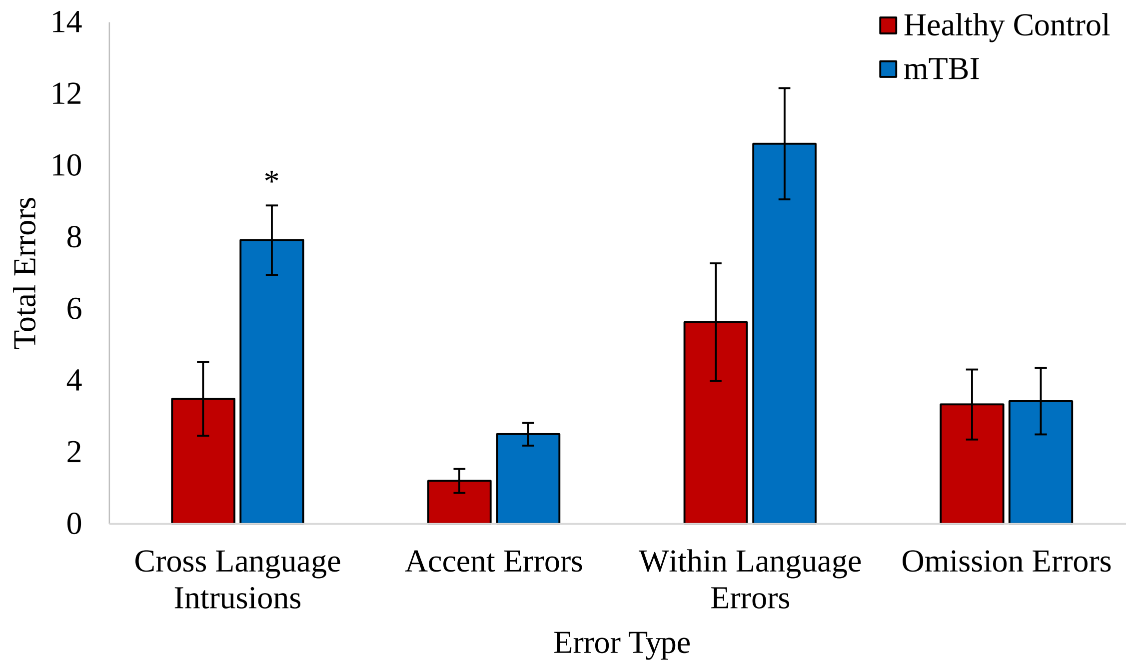

Figure 17. Total errors of each type produced in the reading aloud task by Group. Error bars represent standard errors. *Denotes significantly different from Healthy Controls (p<.013). Group differences for Accent Errors were marginally significant (p=.014).

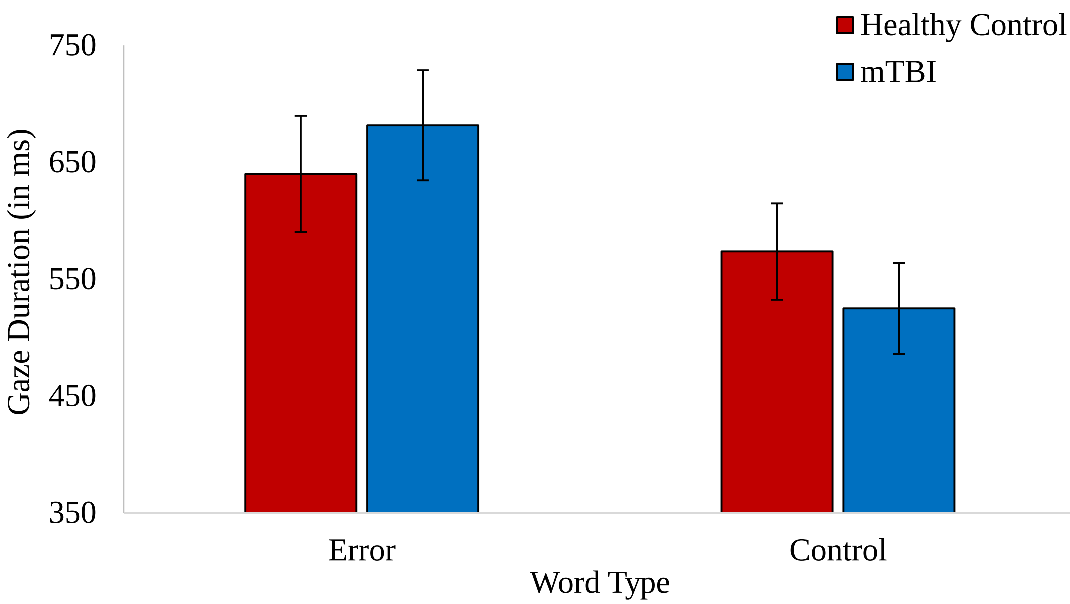

Figure 18. Gaze duration for error words compared correctly produced words. Error bars represent standard errors. *Denotes significantly different from Healthy Controls (p<.025).

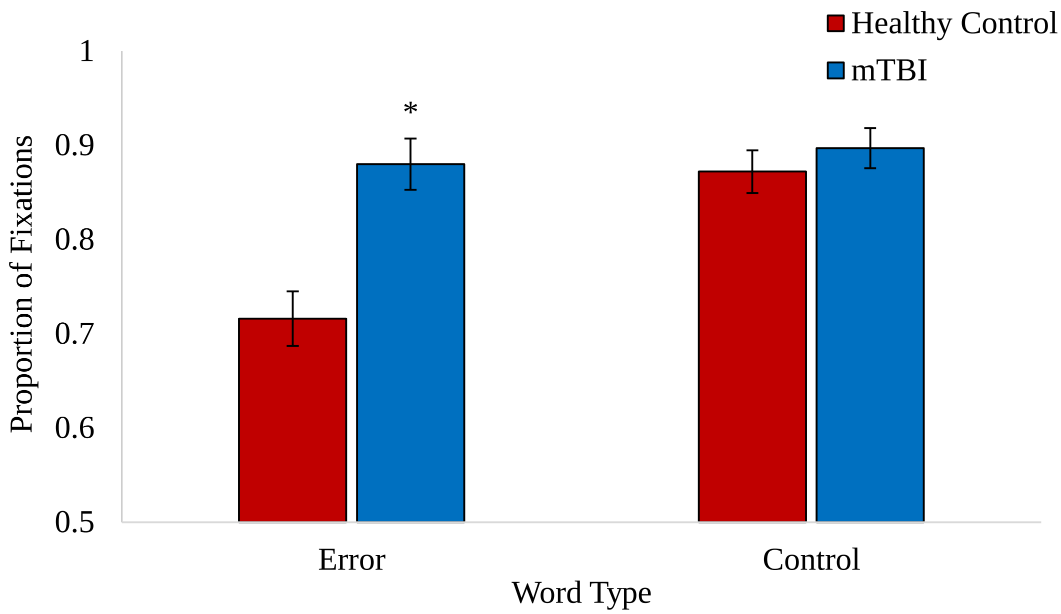

Figure 19. Proportion of fixations when participants produced an error compared to when they produced a similar word correctly. Error bars represent standard errors. *Denotes significantly different from Healthy Controls (p<.025).

APPENDIX A

SUPPLEMENTAL TABLES AND FIGURES

Table A1

Mean Correct Response Times and Accuracy for Flanker Task by Secondary Load for Experiment 1

	No Load	Verbal Load	Nonverbal Load	*M* (*SD*)
Response Times				
Control	438.17 (75.27)	549.87 (149.66)	541.60 (117.84)	510.31 (103.07)
Go/no-go	301.59 (65.81)	354.22 (88.58)	376.32 (88.71)	344.05 (71.96)
Conflict	473.93 (77.25)	572.62 (151.69)	577.01 (120.61)	541.19 (104.15)
Conflict Effect	41.27 (44.84)	23.64 (72.44)	14.92 (52.36)	26.61 (37.17)
M (*SD*)	404.56 (64.81)	493.41 (121.60)	498.31 (98.67)	
Accuracy				
Control	96.90% (4.04%)	95.67% (15.98%)	98.46% (2.37%)	97.01% (5.73%)
Go/no-go	97.92% (2.50%)	98.31% (2.36%)	97.46% (3.19%)	97.90% (1.85%)
Conflict	97.28% (3.32%)	97.92% (3.90%)	98.46% (2.83%)	97.89% (2.05%)
Conflict Effect	0.92% (4.52%)	0.50% (4.71%)	1.42% (4.54%)	0.90% (4.59%)
M (*SD*)	97.37% (2.48%)	97.30% (5.35%)	98.13% (1.91%)	

Note: Standard deviations are in parentheses.

Table A2

Mean Correct Response Times and Accuracy for Flanker Task by Group for Experiment 2

	Healthy Control	mTBI
Response Times		
Control	396.48 (59.17)	418.50 (69.99)
Go/no-go	271.52 (42.08)	323.02 (76.34)
Conflict	414.24 (65.49)	458.42 (103.60)
Conflict Effect	2.30 (15.01)	13.73 (23.84)
Accuracy		
Control	96.95% (3.52%)	96.73% (4.40%)
Go/no-go	96.80% (6.87%)	95.59% (8.18%)
Conflict	97.55% (3.66%)	96.50% (7.68%)
Conflict Effect	0.41% (1.81%)	2.25% (16.02%)

Note: Standard deviations are in parentheses.

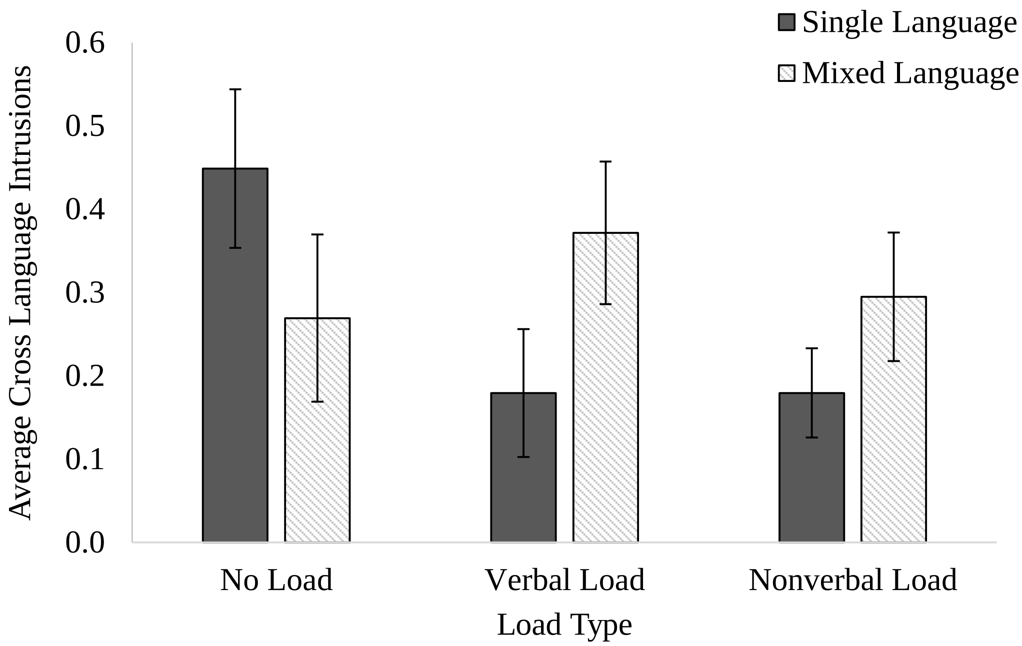

Figure A1. Cross language intrusions for the naming task by Load Type. Error bars represent standard error of the mean. *Denotes significantly different from No Load condition (*p*<.017).

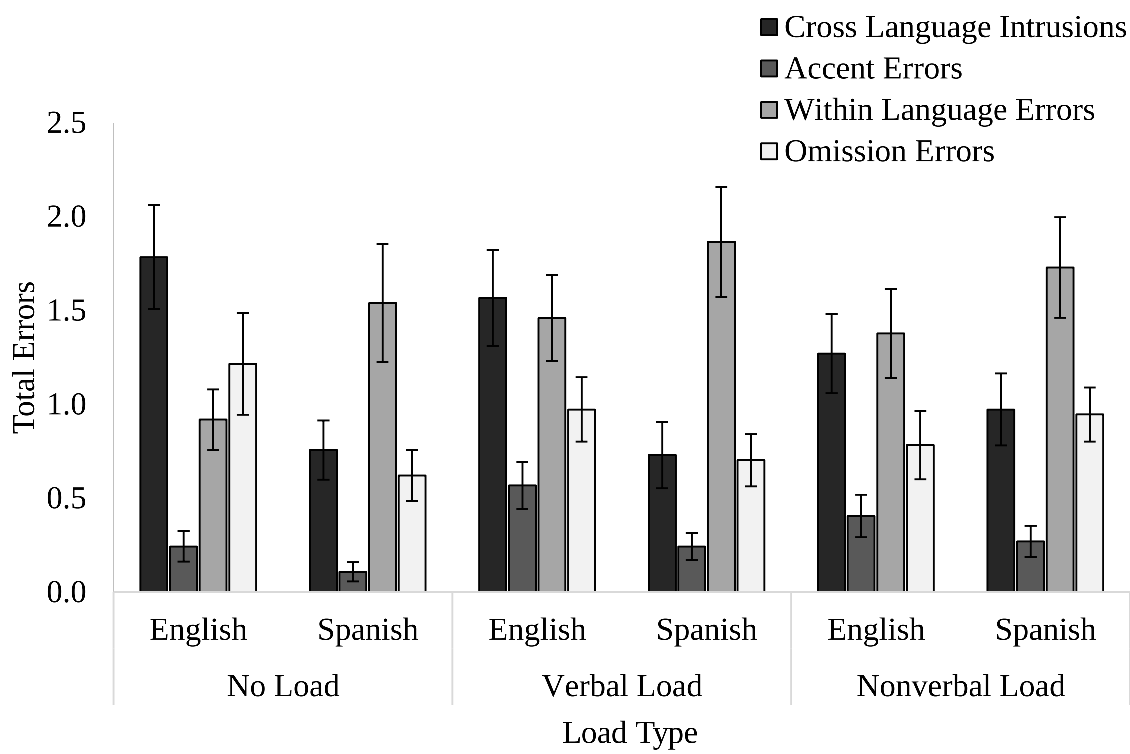

Figure A2. Total errors for the reading aloud task by Load Type and Target Language. Error bars represent standard error of the mean. *Denotes significantly different from No Load condition (*p*<.003).

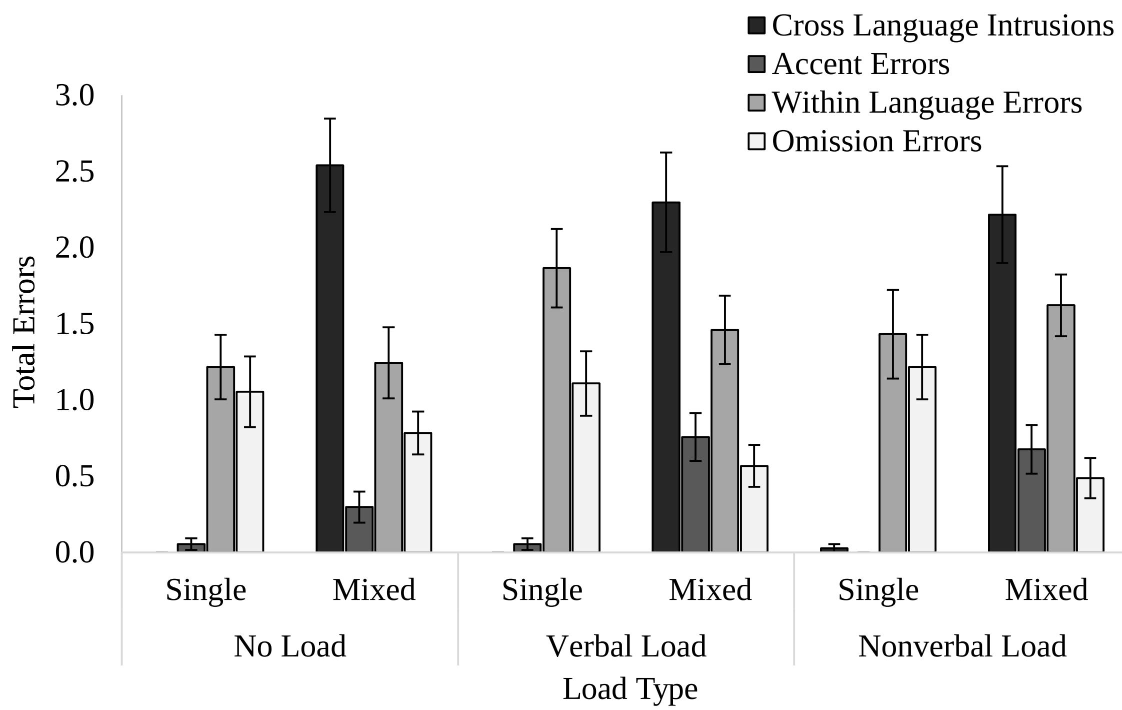

Figure A3. Total errors for the reading aloud task by Load Type and Mixing. Error bars represent standard error of the mean. *Denotes significantly different from No Load condition (*p*<.003).

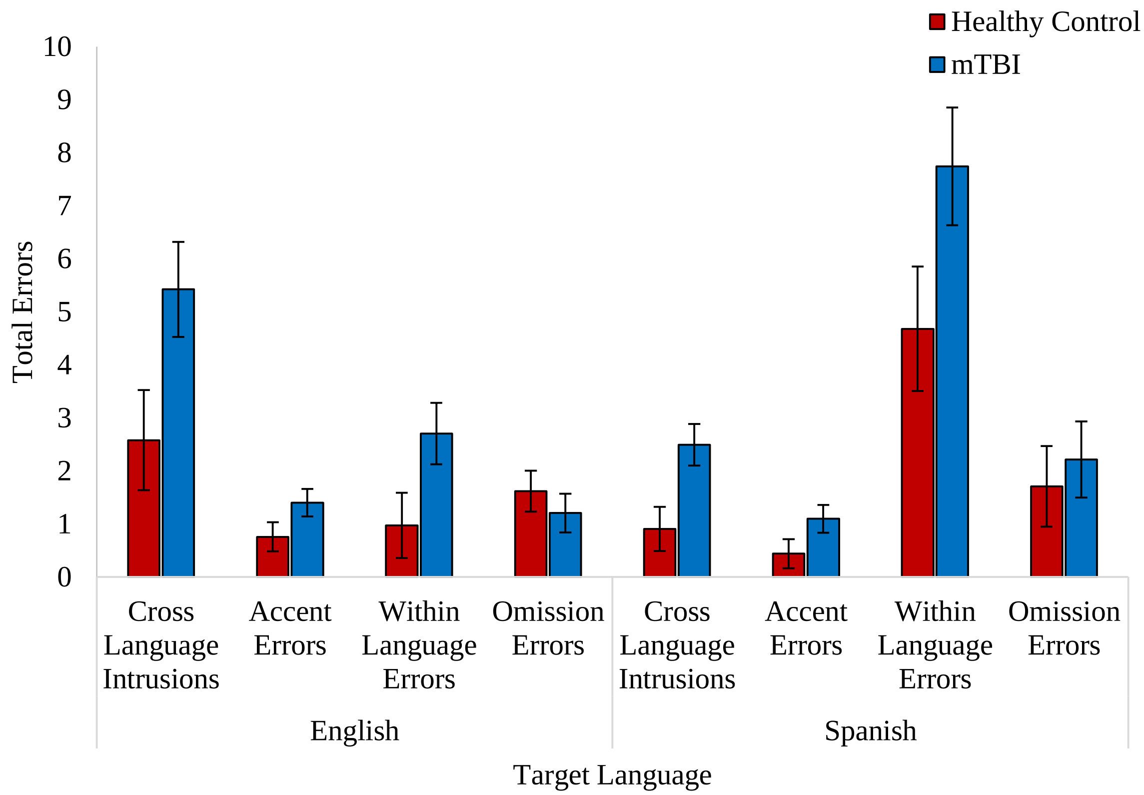

Figure A4. Total errors for the reading aloud task by Group and Target Language. Error bars represent standard error of the mean. *Denotes significantly different from Healthy Controls (p<.006).

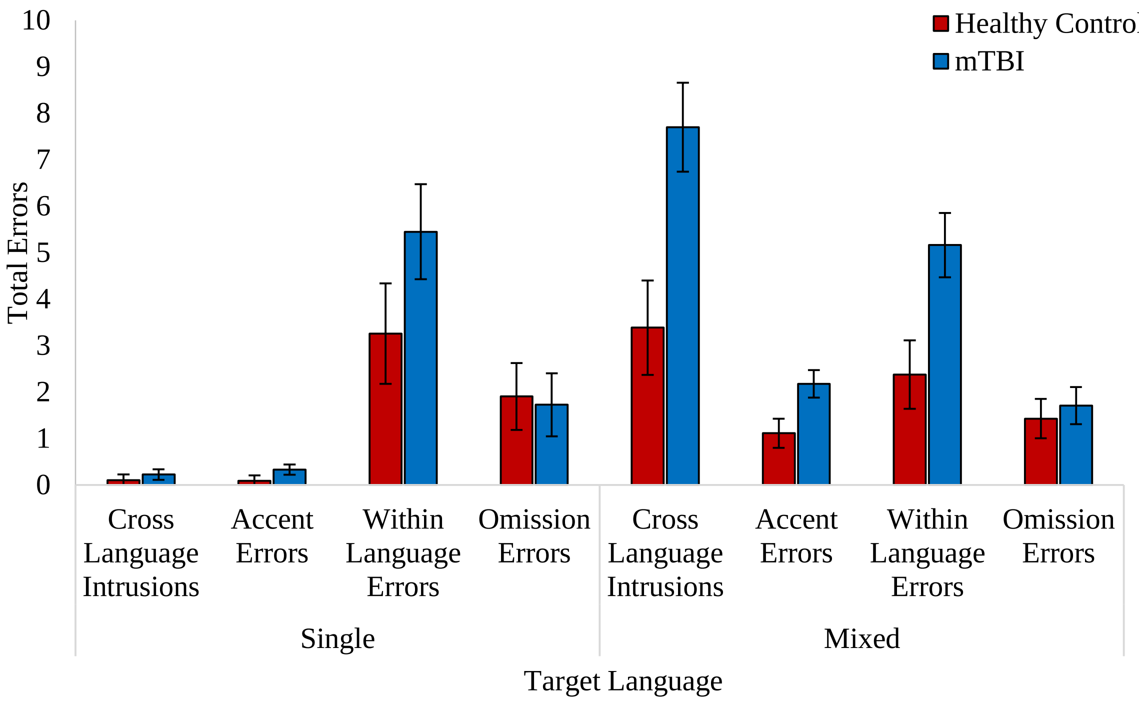

Figure A5. Total errors for the reading aloud task by Group and Mixing. Error bars represent standard error of the mean. *Denotes significantly different from Healthy Controls (p<.006).

APPENDIX B

WORD LISTS FOR OPERATION SPAN TASKS USED IN EXPERIMENT 1 AND 2

English		Spanish	
tall	task	loco	triste
wheel	remove	salud	leer
allow	send	jugar	reloj
dance	seat	silla	espejo
skin	garden	frío	gusto
rich	broken	comida	caer
mine	hat	vacío	barco
fresh	drink	malo	oír
break	band	dormir	ritmo
fat	train	lluvia	cuello
smile	dust	ojo	perro
bear	fort	nariz	pobre
sweet	ideal	leche	amiga
fill	dear	feliz	buscar
king	camp	tarea	azul
avoid	begin	calor	baño
desk	dinner	igual	duro
minute	page	tío	juez
bridge	nice	caja	nota
carry	drop	mirar	comer
model	weight	pelo	niña
enter	grow	rojo	peso
roof	spot	sala	ropa
pale	round	vale	humo

APPENDIX C

IMAGES USED IN CONFRONTATIONAL NAMING TASK IN EXPERIMENTS 1 AND 2
































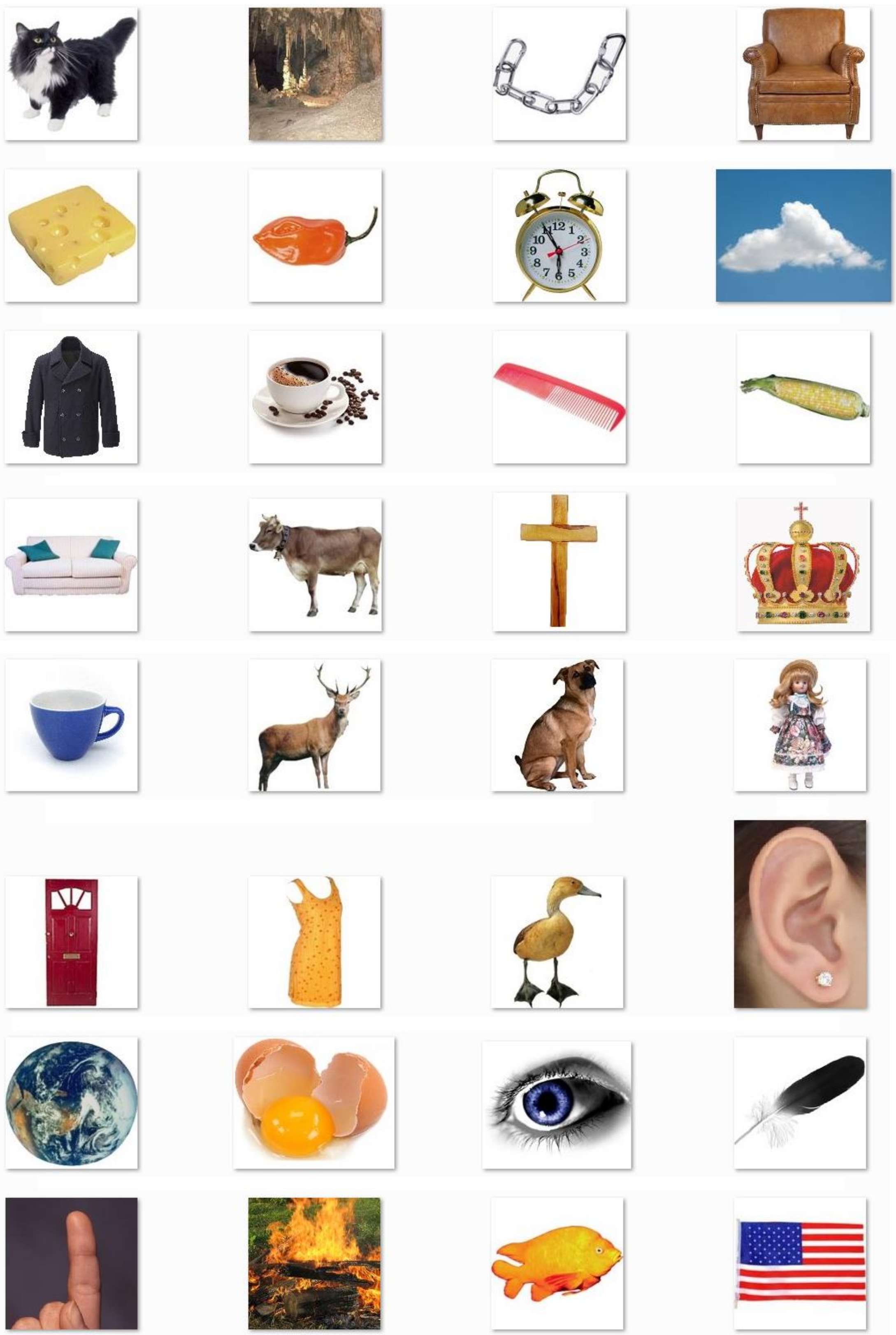

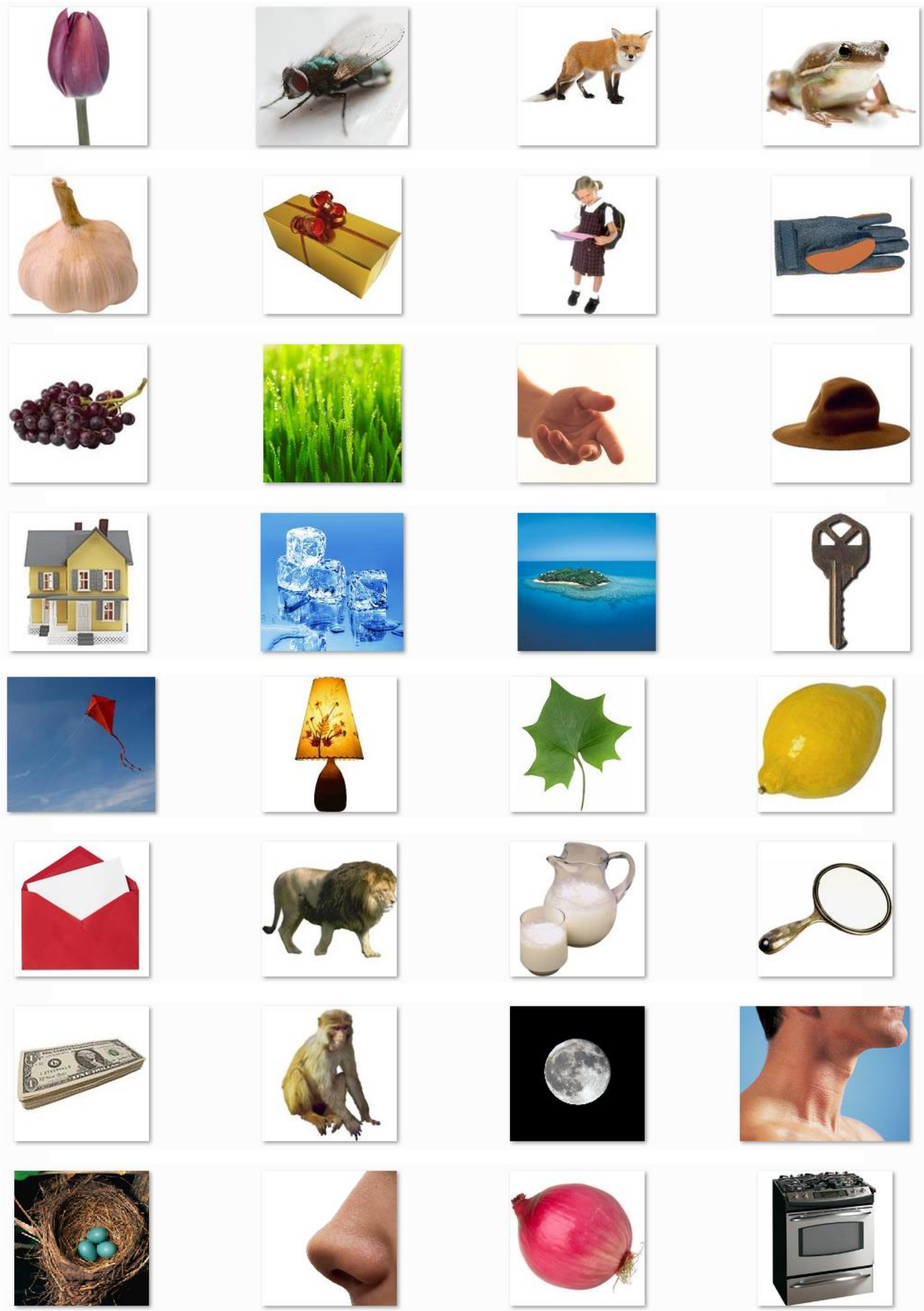

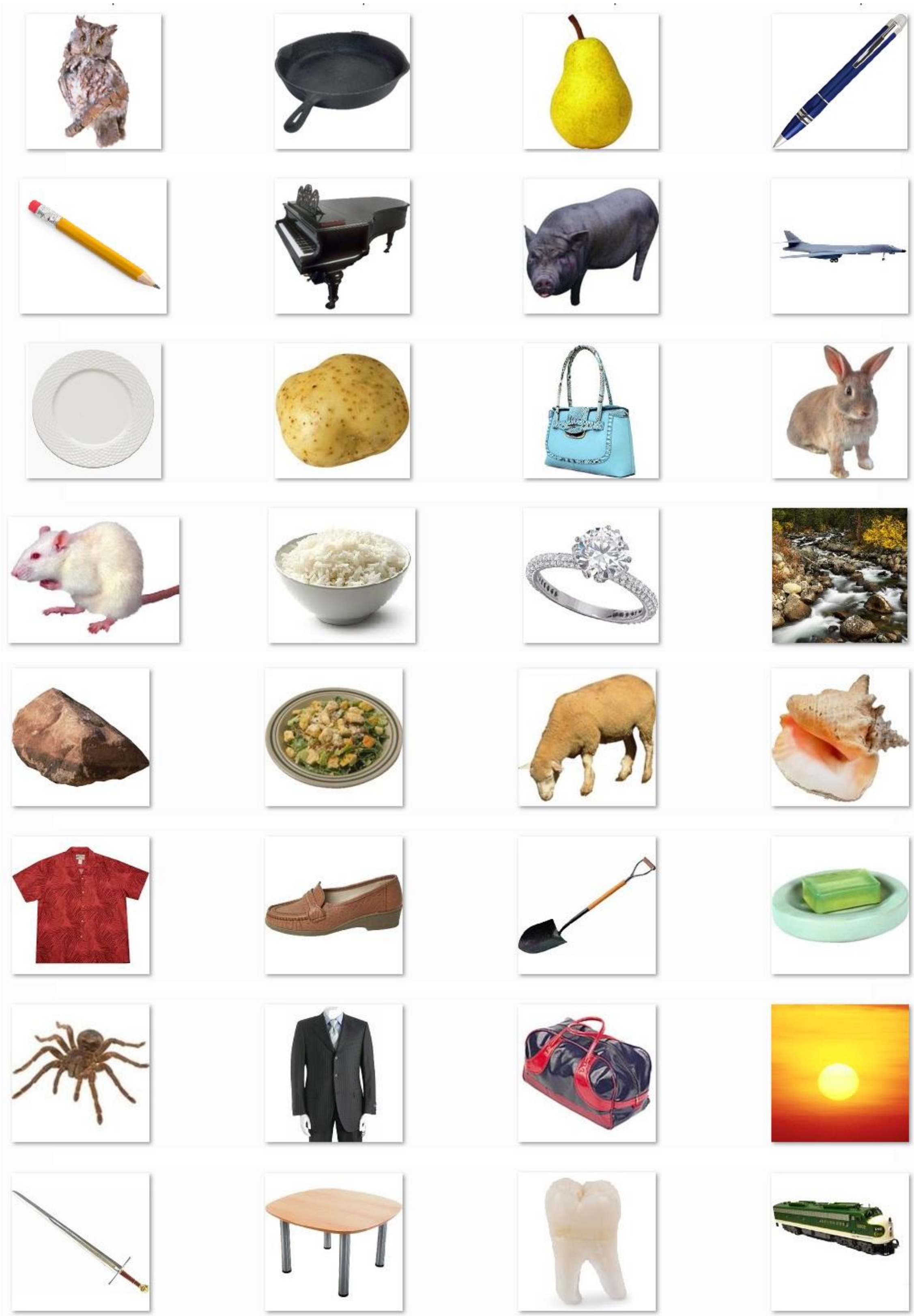










APPENDIX D

INSTITUTIONAL REVIEW BOARD APPROVAL

ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Tamiko Azuma
Speech and Hearing Science
480/965-9455
TAMIKO.AZUMA@asu.edu

Dear Tamiko Azuma:

On 8/19/2014 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Executive Function and Language Control in Bilinguals
Investigator:	Tamiko Azuma
IRB ID:	STUDY00001390
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Informed Consent, Category: Consent Form; • Azuma Ratiu Protocol Revised, Category: IRB Protocol; • Banihashemi CITI Training, Category: Non-ASU human subjects training (if taken within last 3 years to grandfather in); • Azuma CITI Training, Category: Non-ASU human subjects training (if taken within last 3 years to grandfather in); • Ratiu CITI Training, Category: Non-ASU human subjects training (if taken within last 3 years to grandfather in); • Recruitment Flyer, Category: Recruitment Materials; • SONA Systems Description 2.docx, Category: Recruitment Materials; • Questionnaire, Category: Technical materials/diagrams; • Sample Tasks, Category: Technical materials/diagrams;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 8/19/2014.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Ileana Ratiu
Setarae Banihashemi
Julie Liss
Stephen Goldinger
Ileana Ratiu

APPROVAL: EXPEDITED REVIEW

Tamiko Azuma
SNHP - Speech and Hearing Sciences
480/965-9455
TAMIKO.AZUMA@asu.edu

Dear Tamiko Azuma:

On 2/20/2014 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Executive Function and Language Control Deficits in Bilinguals with Traumatic Brain Injury
Investigator:	Tamiko Azuma
IRB ID:	STUDY00000582
Category of review:	(7)(b) Social science methods, (7)(a) Behavioral research
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Informed Consent, Category: Consent Form; • Acquired Brain Injury Deficits in Bilinguals_Azuma_Ratiu, Category: IRB Protocol; • Bilingual Language and Experience Questionnaire, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Neurogenic Case History, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Sample Assessments and Tasks, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Ileana Ratiu State License , Category: Other (to reflect anything not captured above); • Ileana Ratiu National License , Category: Other (to reflect anything not captured above);

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	• HIPAA Disclosure, Category: Other (to reflect anything not captured above); • Instructions for Contact, Category: Participant materials (specific directions for them); • Recruitment Flyer, Category: Recruitment Materials;

The IRB approved the protocol from 2/20/2014 to 2/19/2015 inclusive. Three weeks before 2/19/2015 you are to submit a completed "FORM: Continuing Review (HRP-212)" and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 2/19/2015 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Ileana Ratiu
Julie Liss
Stephen Goldinger
Ileana Ratiu